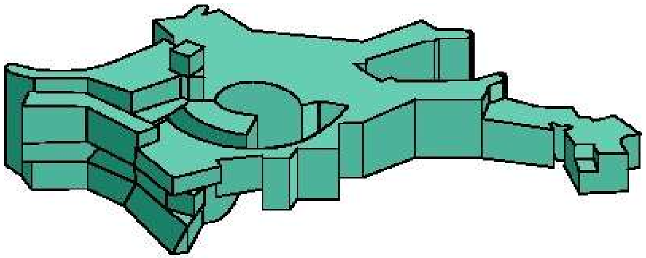


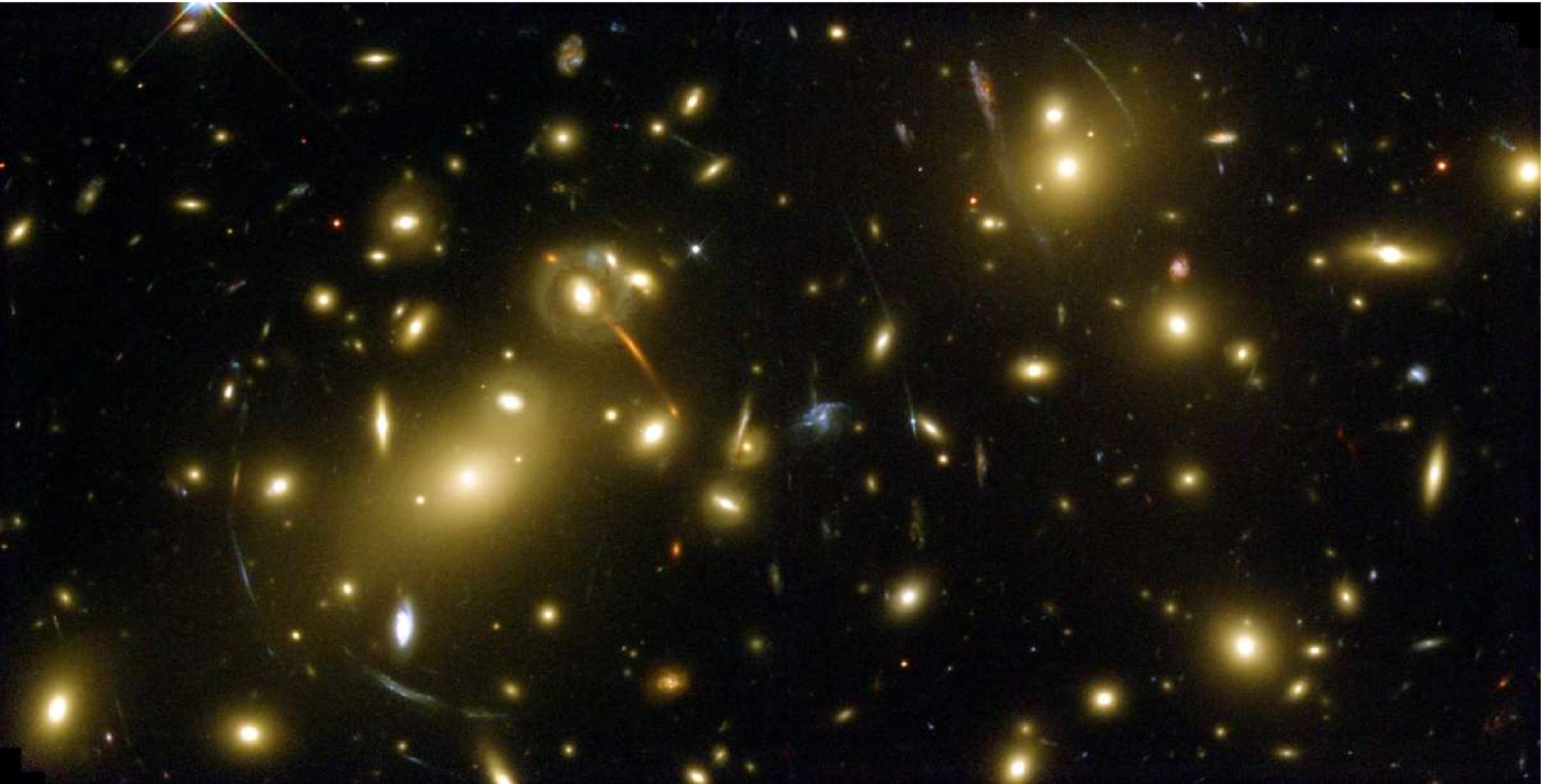
Sackler Lecture in Astrophysics
Princeton, April 3, 2003

The Formation and Evolution of Galaxy Clusters

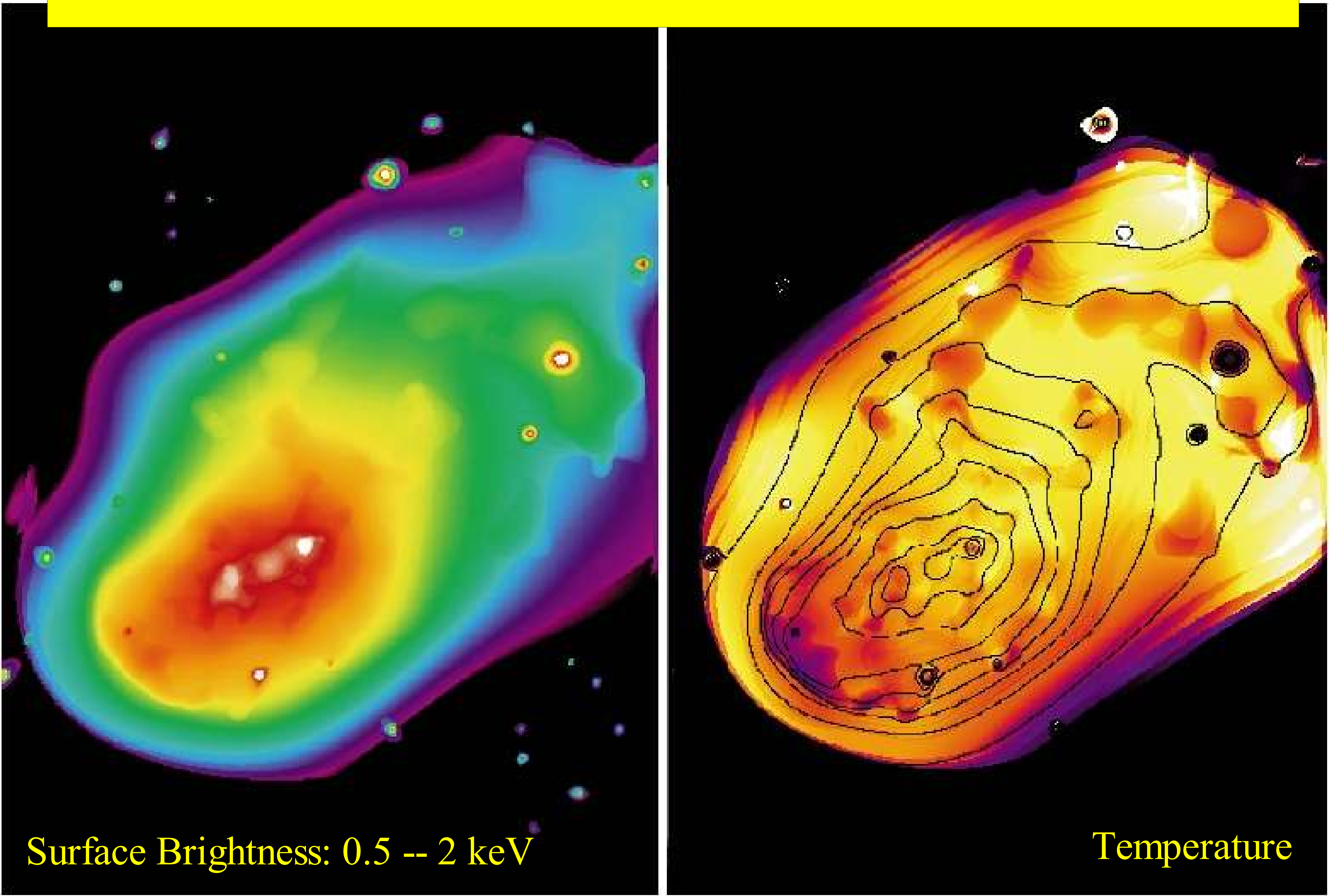
Simon D.M. White
Max Planck Institute for Astrophysics

Hubble Space Telescope image of a galaxy cluster

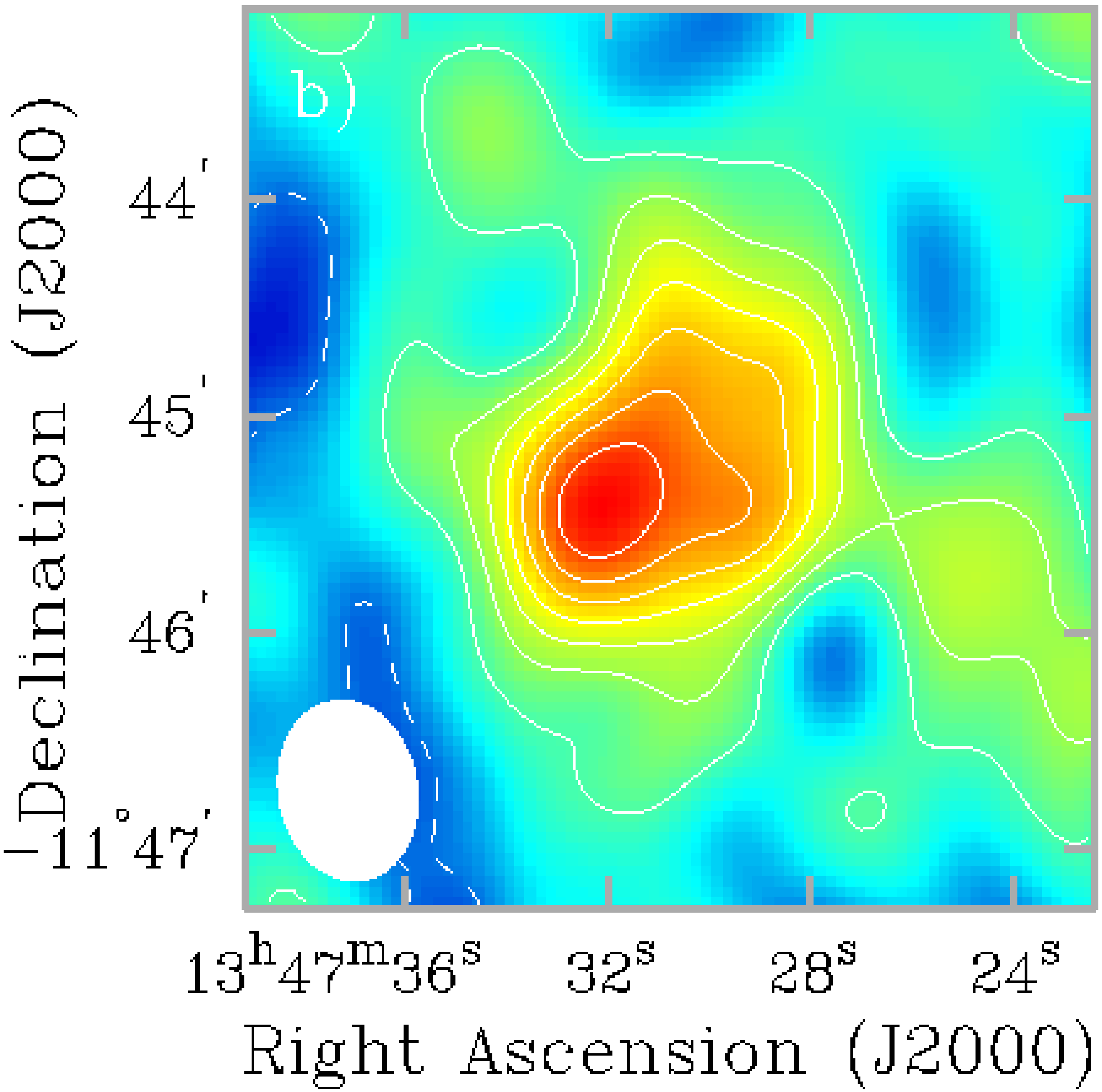
Abell 2218 z=0.17



Rosat X-ray image of the cluster Abell 3667



Cluster shadows on the microwave background



- Compton upscattering of CMB photons by e⁻ in the hot intracluster gas leaves a deficit in the background

  Sunyaev-Zeldovich effect

- Map made using the BIMA interferometer

  Carlstrom et al 2001

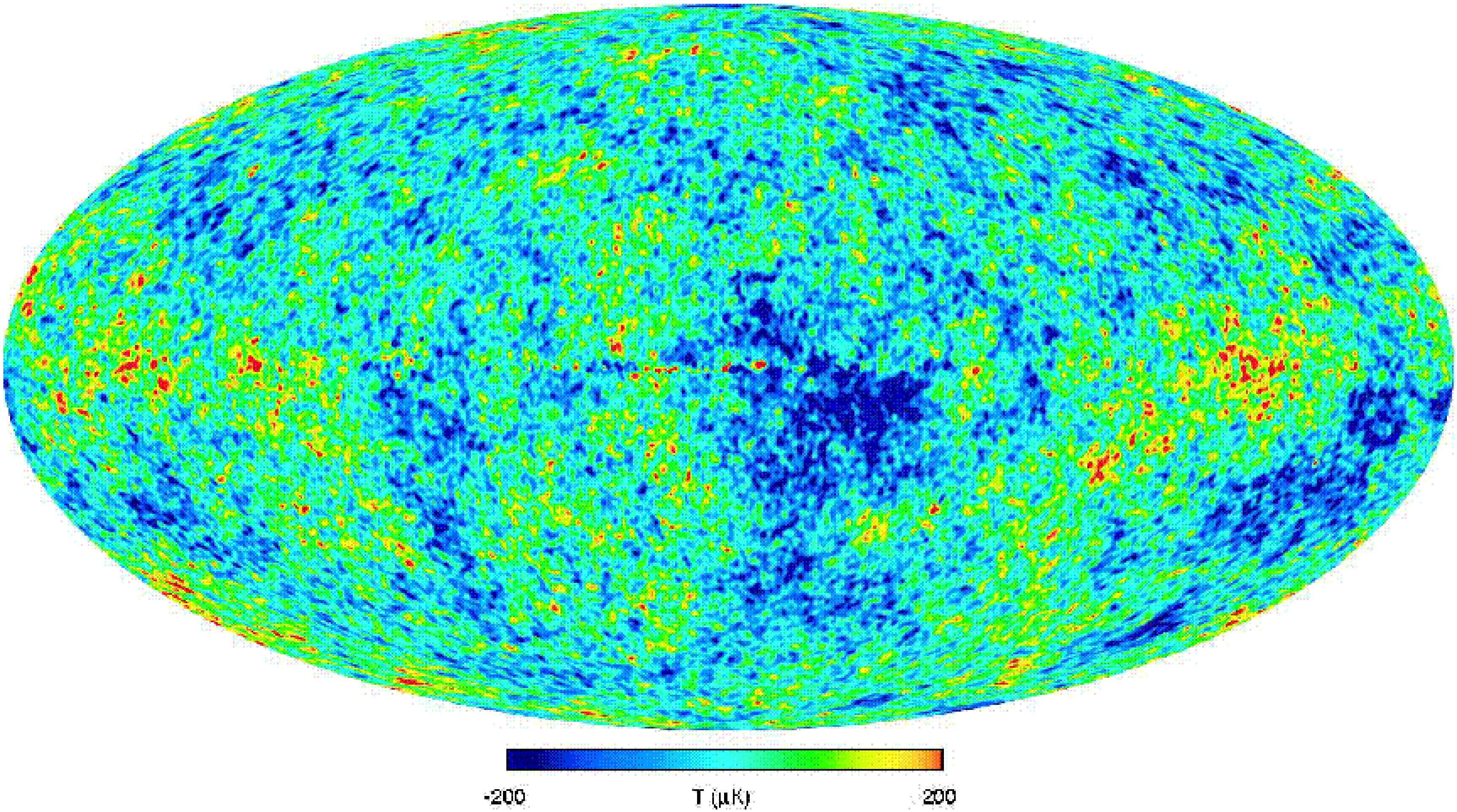
Galaxy clusters: some characteristics

- Total masses: $\sim 10^{15} M_\odot$
- Mass fraction in stars: $\sim 2\%$
- Mass fraction in diffuse, X-ray emitting plasma: $\sim 15\%$
- Number of galaxies brighter than the Milky Way: ~ 50
- Radius: ~ 2 Mpc
- Mean density: $\sim 200 \times \rho_{\mathrm{crit}}$
- Typical galaxy motion through the cluster: ~ 1500 km/s
- Typical distance between clusters: ~ 100 Mpc
- Fraction of all cosmic mass in clusters: $\sim 2\%$

A standard paradigm for cosmic evolution

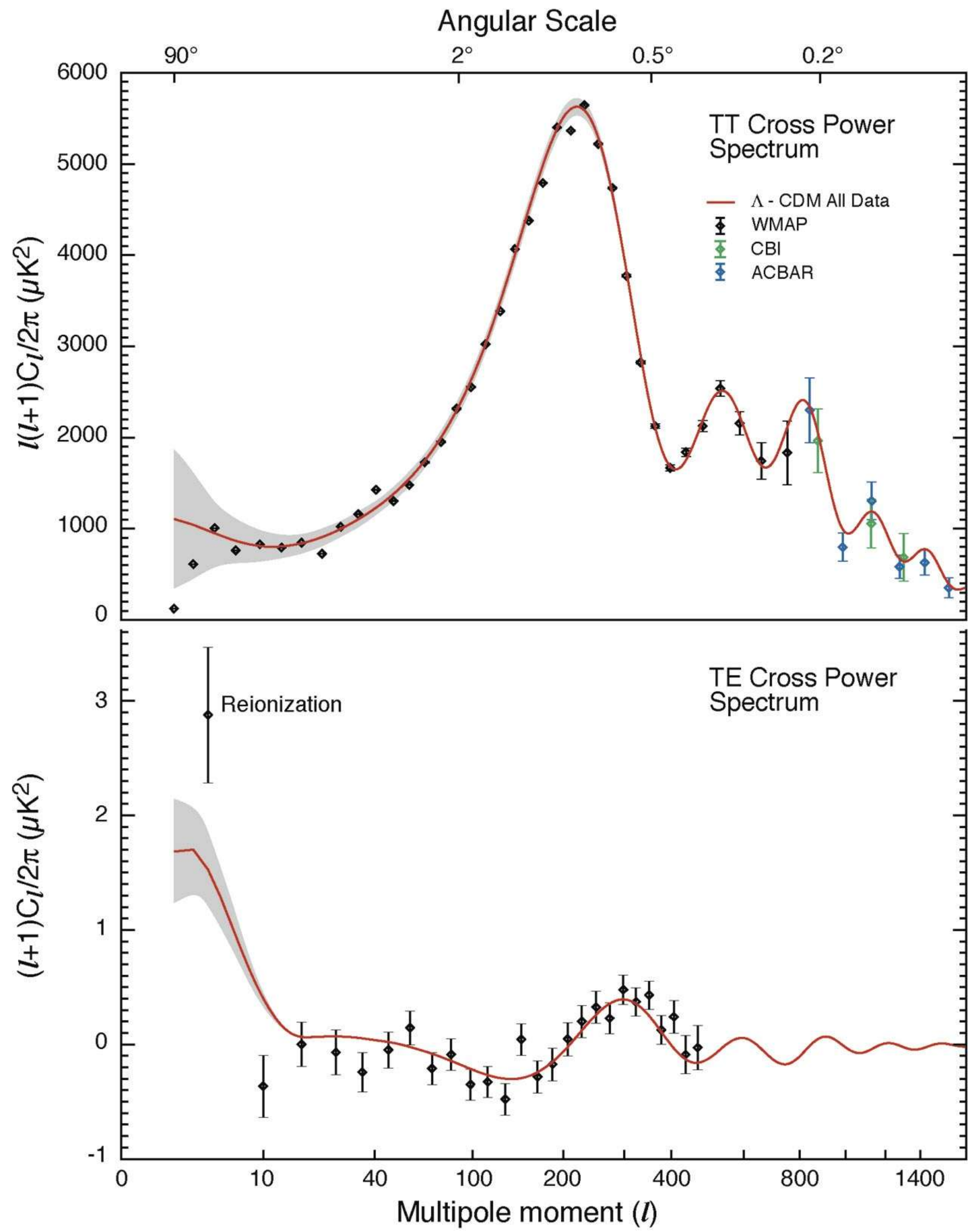
- The Universe began about 14 Gyrs ago in an almost uniform and isotropic Hot Big Bang
- All structure originated as zero-point fluctuations of a free quantum field during an early ($\sim 10^{-30}$s) period of inflation
- The current mass/energy content of the Universe is:
  - -- 70% 'dark energy' (cosmological constant or quintessence?)
  - -- 30% cold dark matter (axions, neutralinos,...?)
  - -- 4% baryonic matter (of which 1/10 lies in galaxies)
  - -- 0.1% neutrinos
  - -- 0.01% radiation (the cosmic microwave background)
- Structure growth is driven (almost) entirely by gravity
- Galaxies form when gas cools and condenses within the potential wells of dark matter 'halos'

The *WMAP* of the whole CMB sky



Bennett et al 2003

The Emergence of the Cosmic Initial Conditions



- Temperature-temperature and temperature-E-polariz'n power spectra for *WMAP* and interferometers

- Best ΛCDM model has:

  (Bennett et al 2003)

  t_o= 13.7±0.2 Gyr

  h=0.71±0.03 σ_8=0.84±0.04

  Ω_t=1.02±0.02 Ω_m=0.27±0.04

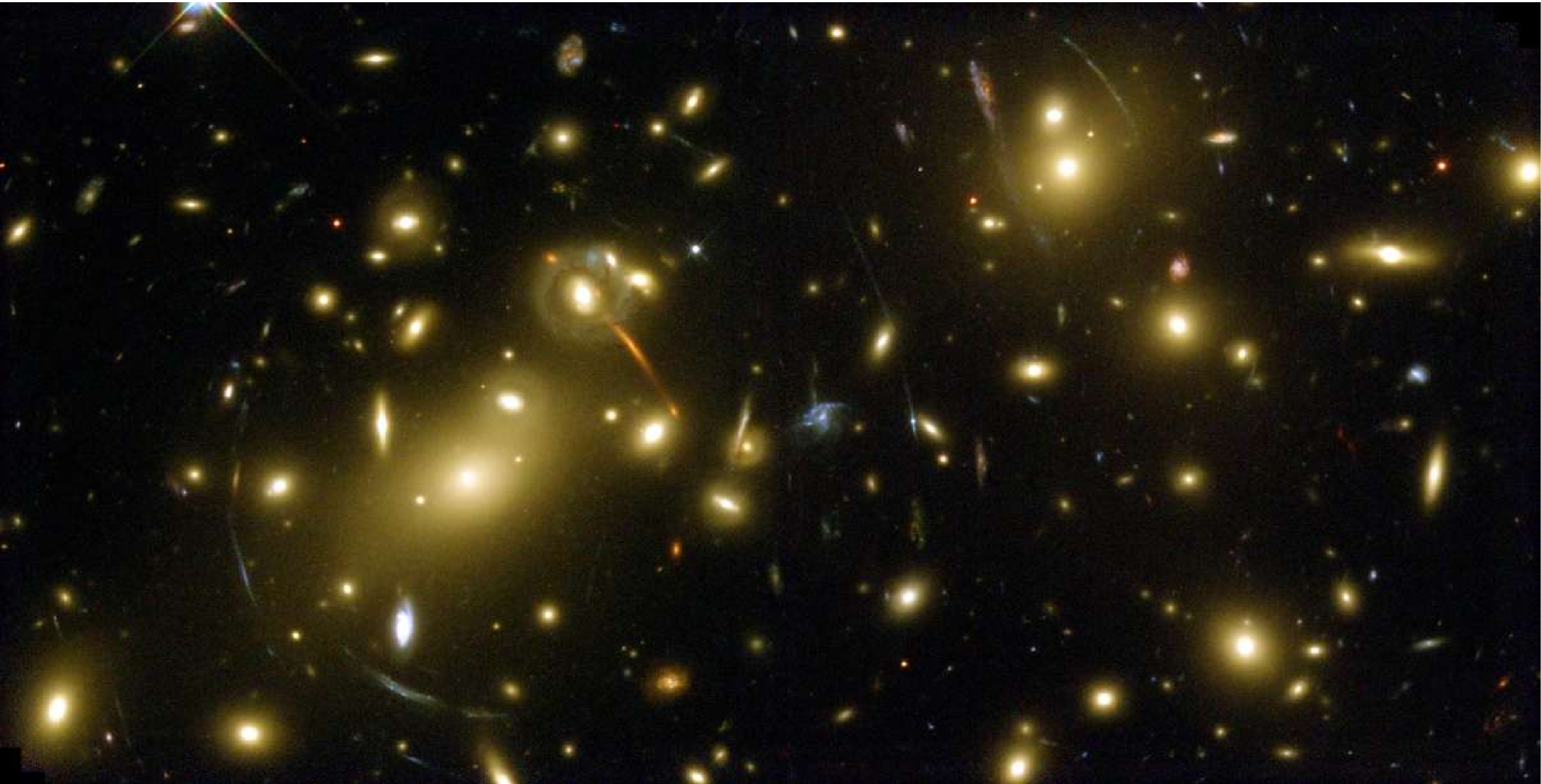
  Ω_b=0.044±0.004

  τ_e=0.17±0.07

- Parameters in excellent agreement with earlier data

Gravitational lensing by a galaxy cluster

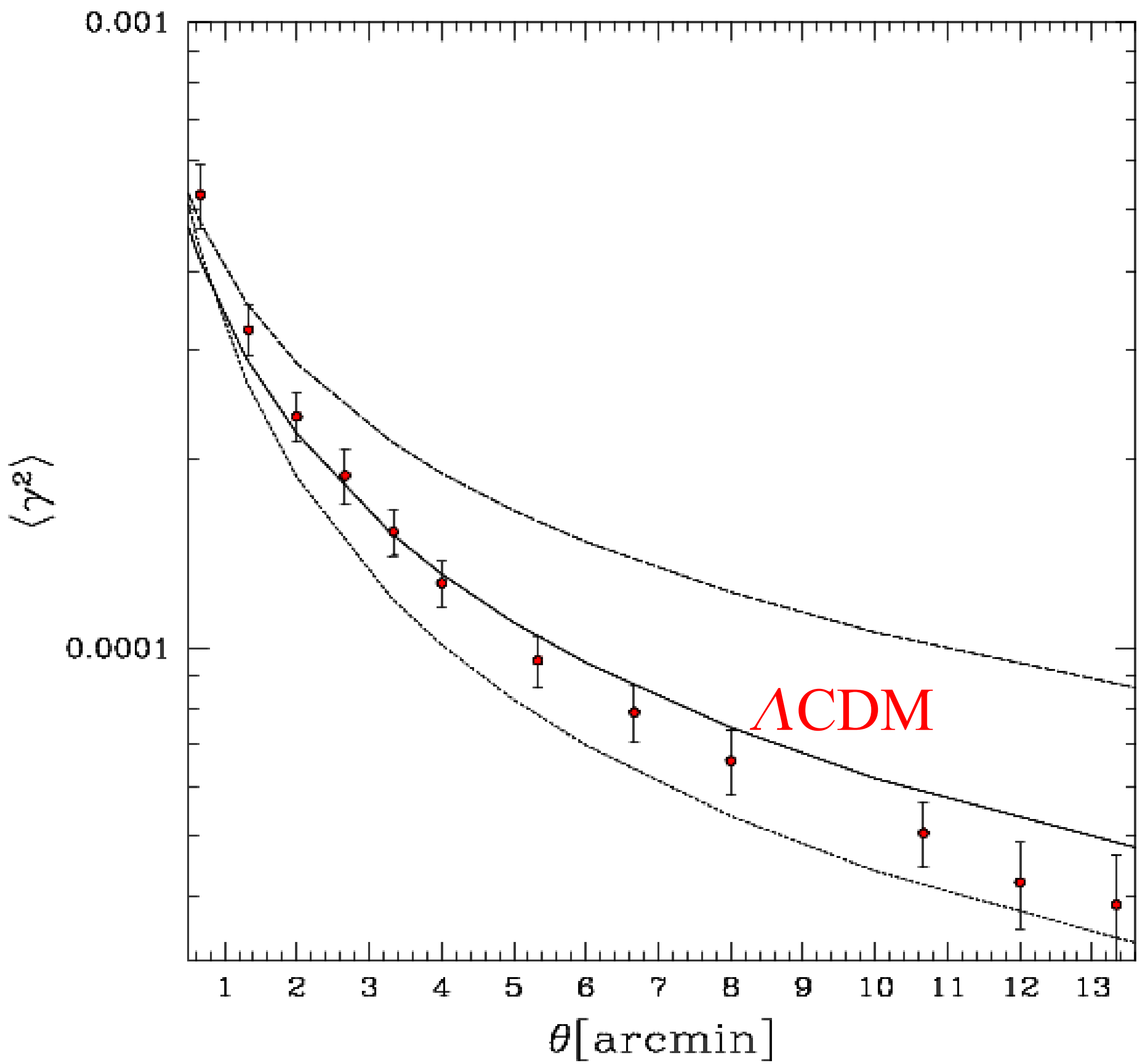
Abell 2218   z=0.17



A measurement of dark matter clustering

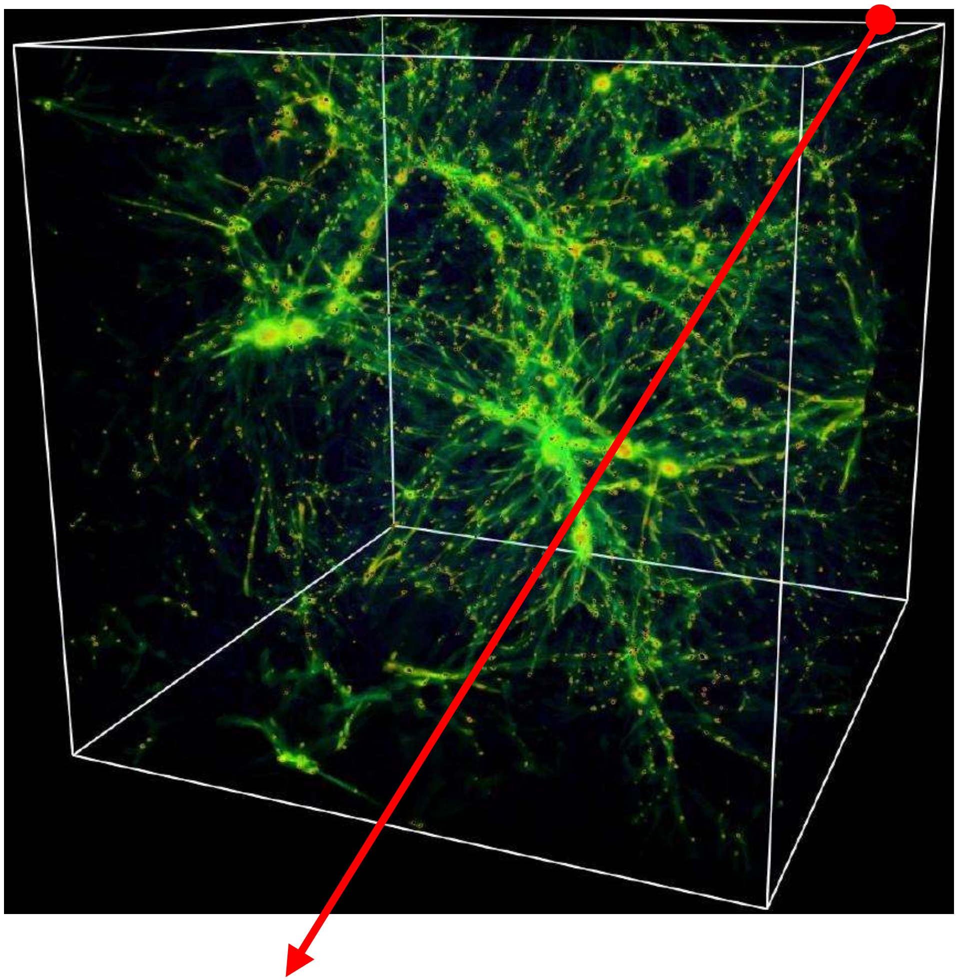
Van Waerbeke et al 2001

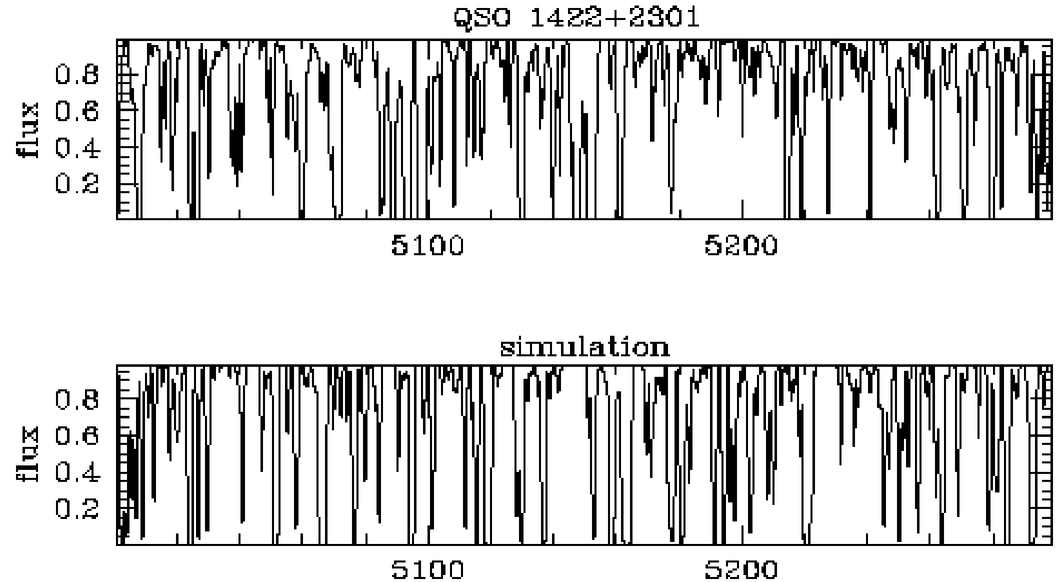
- $<\gamma^2>$ is the mean square gravitational shear of background galaxy images within circles of radius ϑ.
- It is proportional to the mean square lensing mass within these circles
- Signal on small scales is dominated by *galaxy* halos at z~0.4
- Fitting requires nonlinear ΛCDM prediction

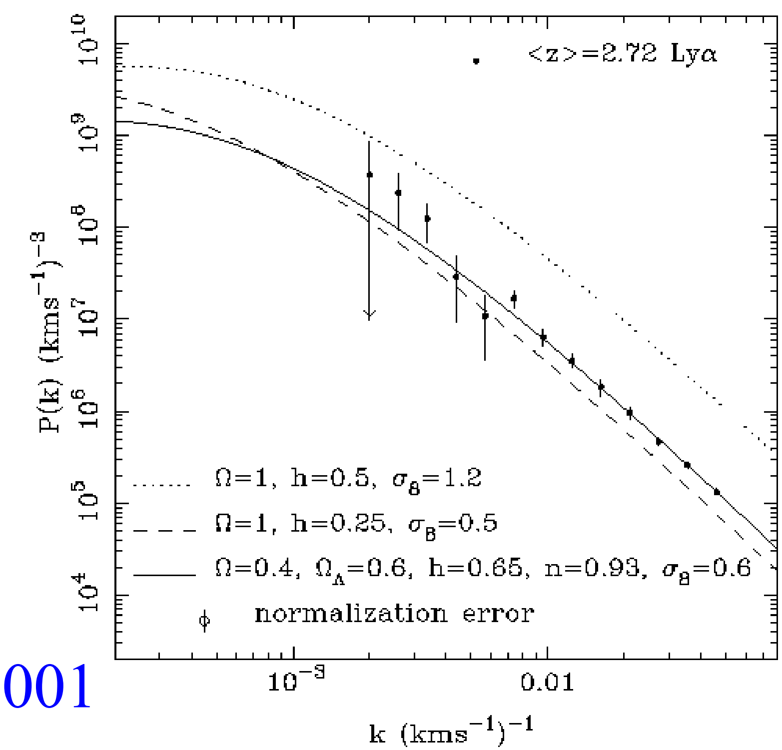


Mapping the intergalactic medium

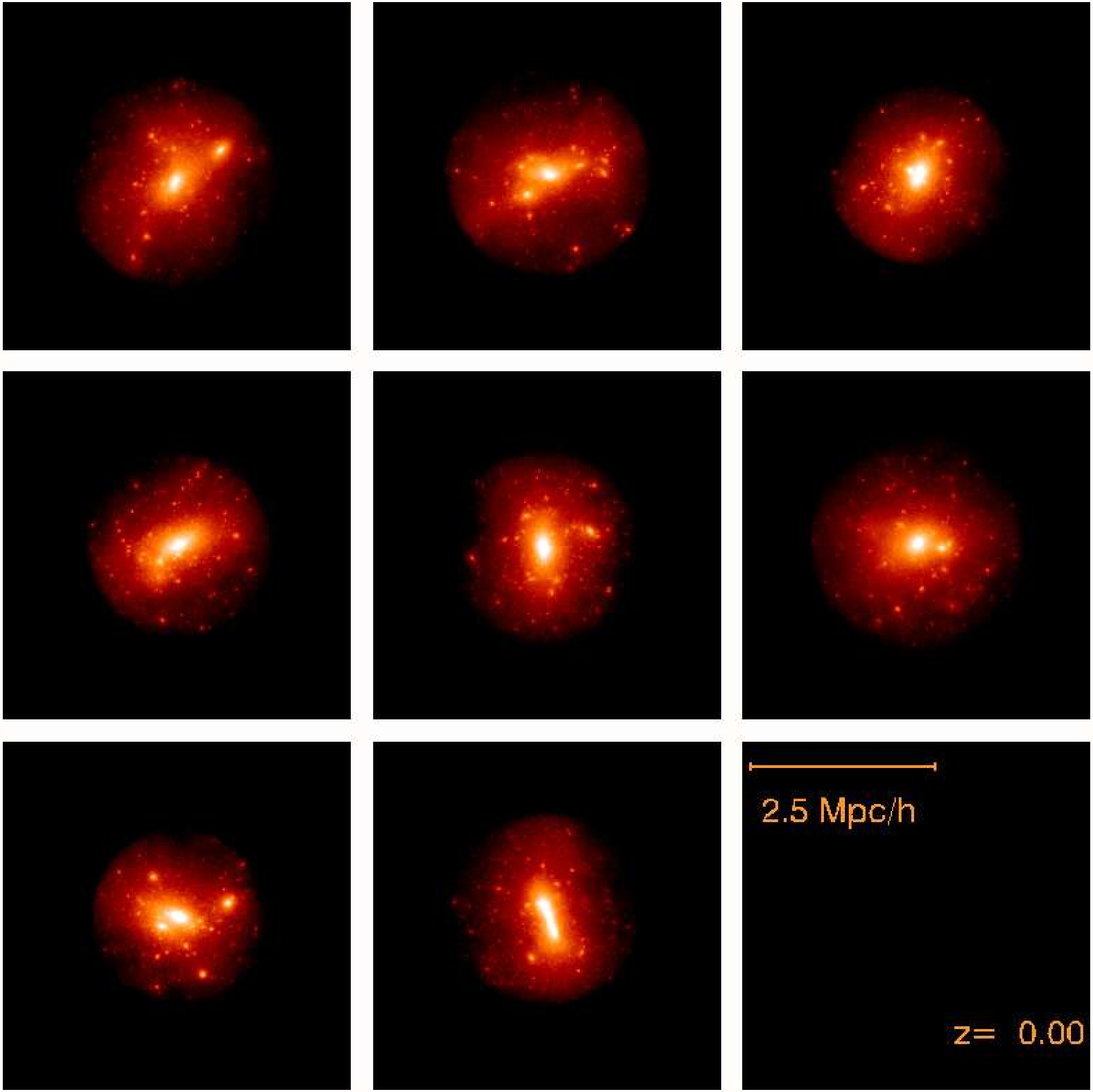
Cen et al 2001





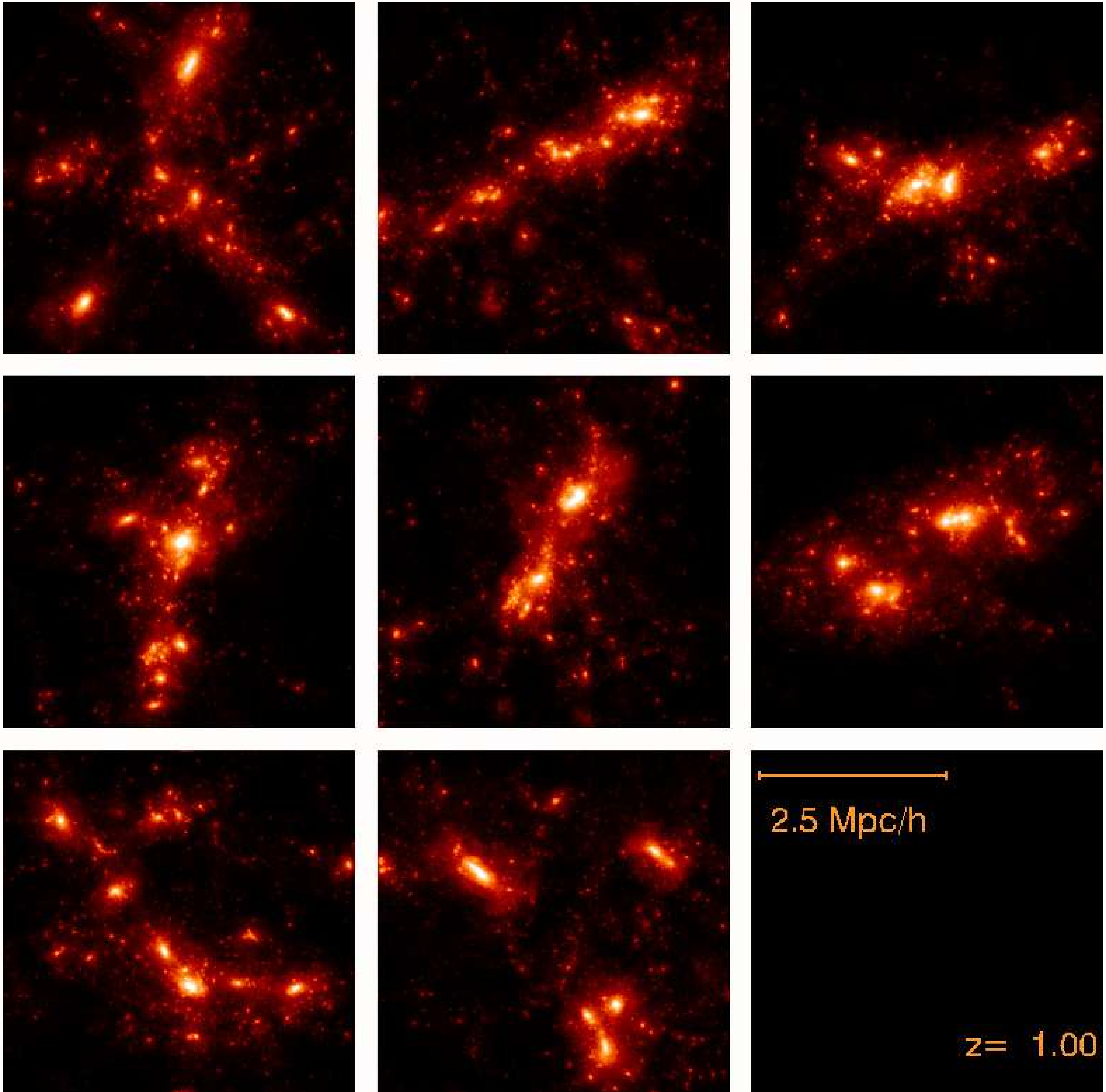


Croft et al 2001



Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass $\sim 10^{15}\ M_\odot$
- Only DM within R_{200} at $z = 0$ is shown



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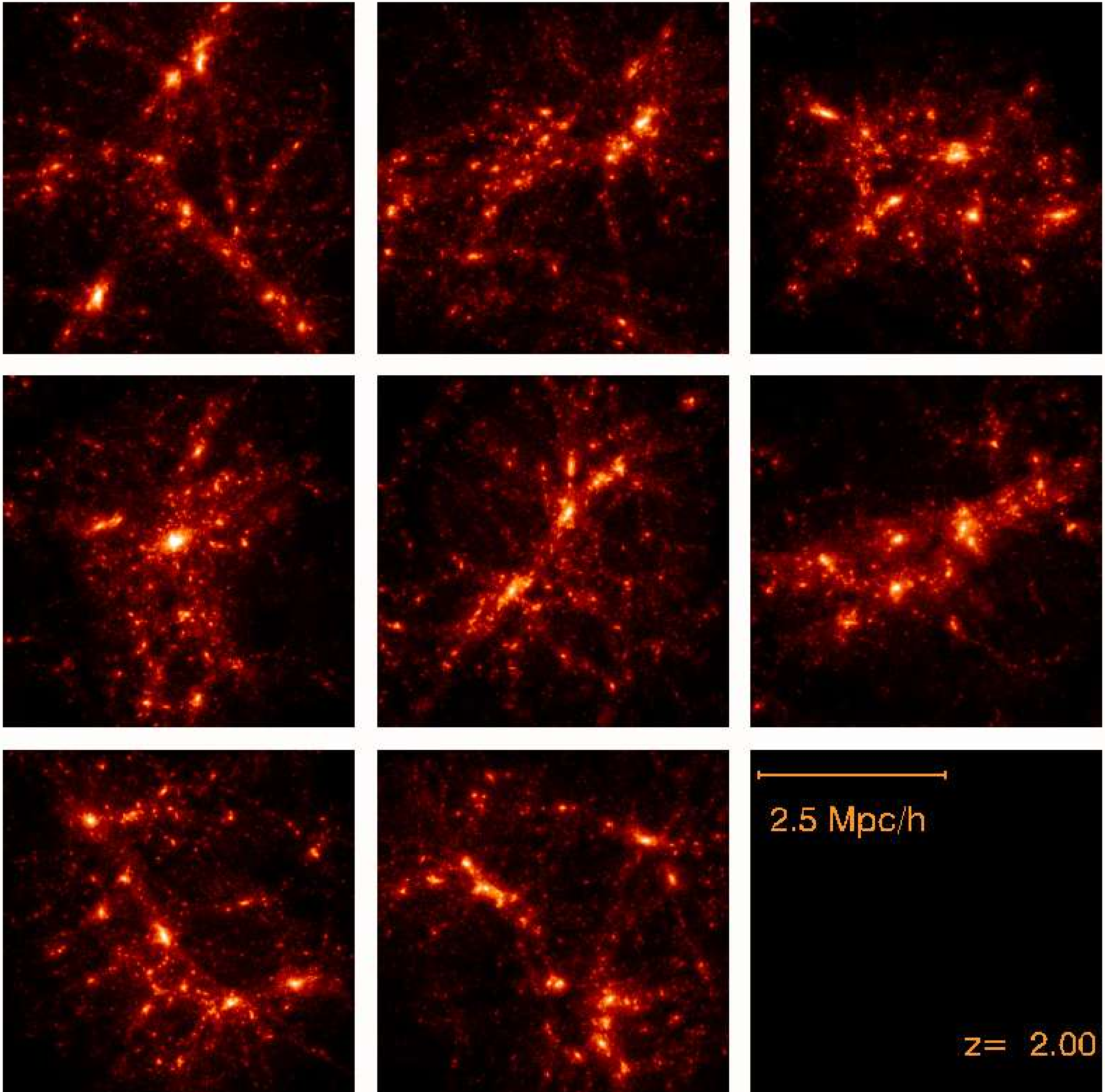
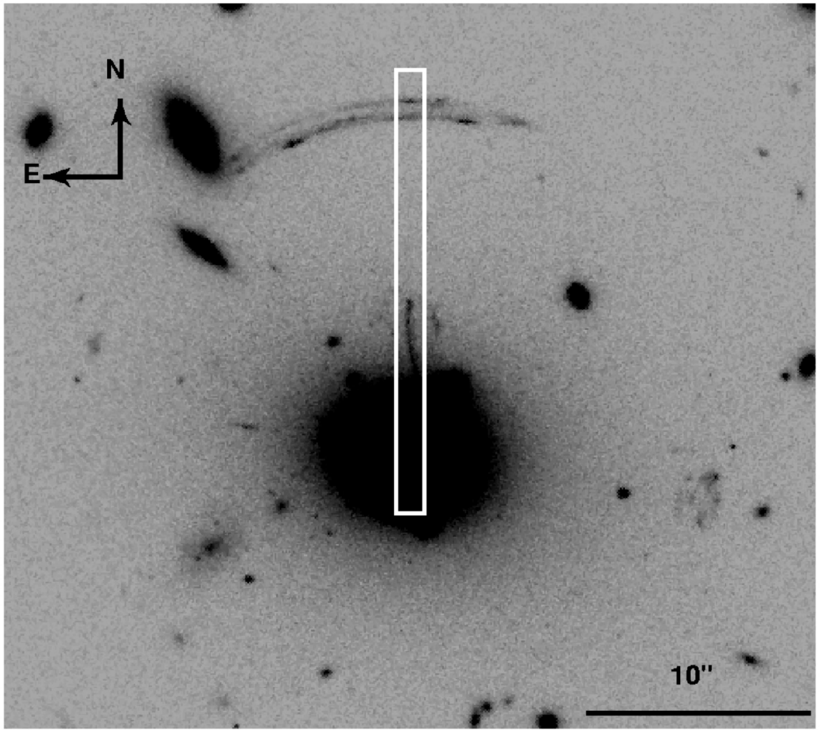


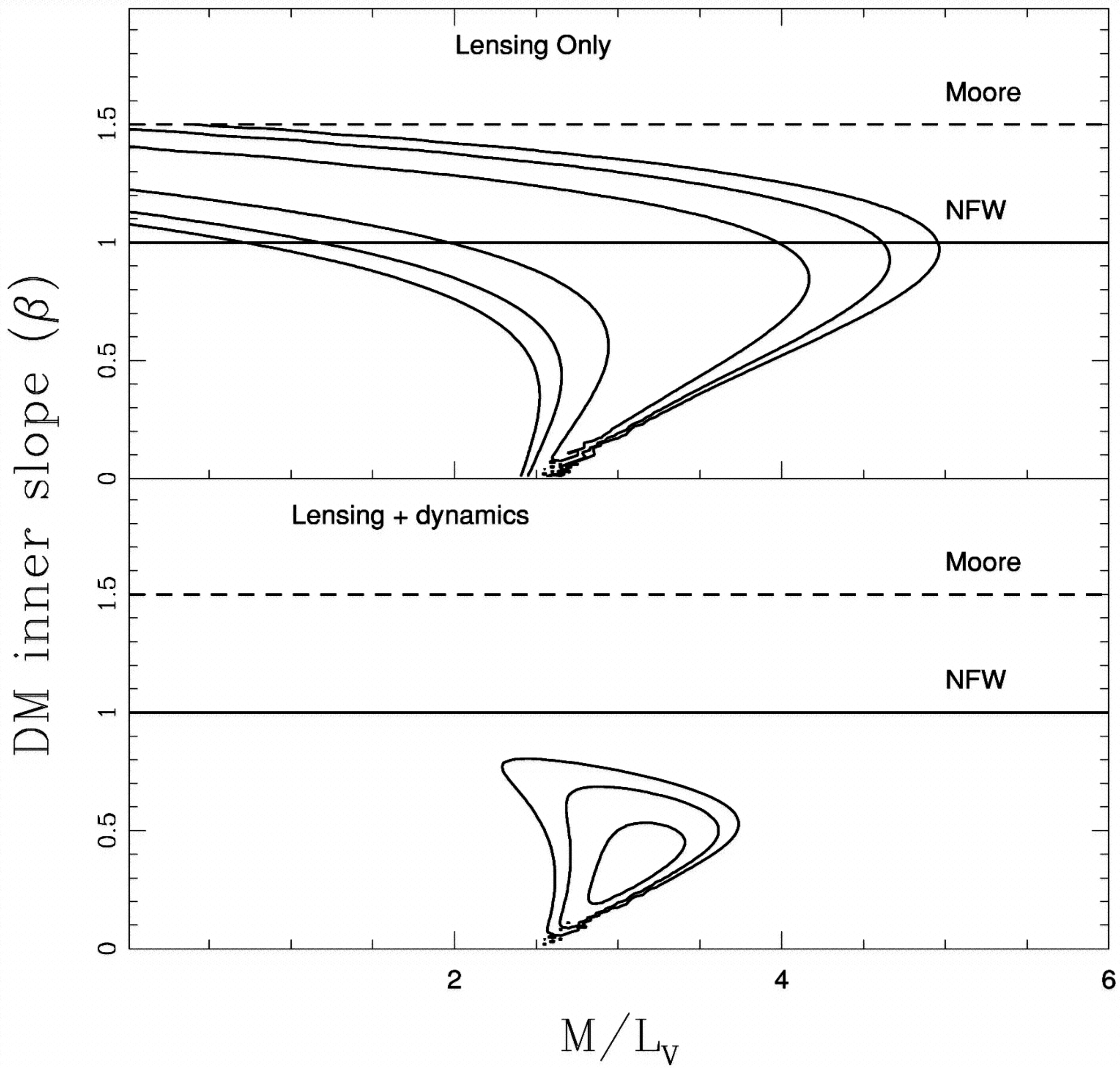
Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass ~10^{15} $M_\odot$
- Only DM within R_{200} at $z = 0$ is shown

Constraining DM properties with strong lensing

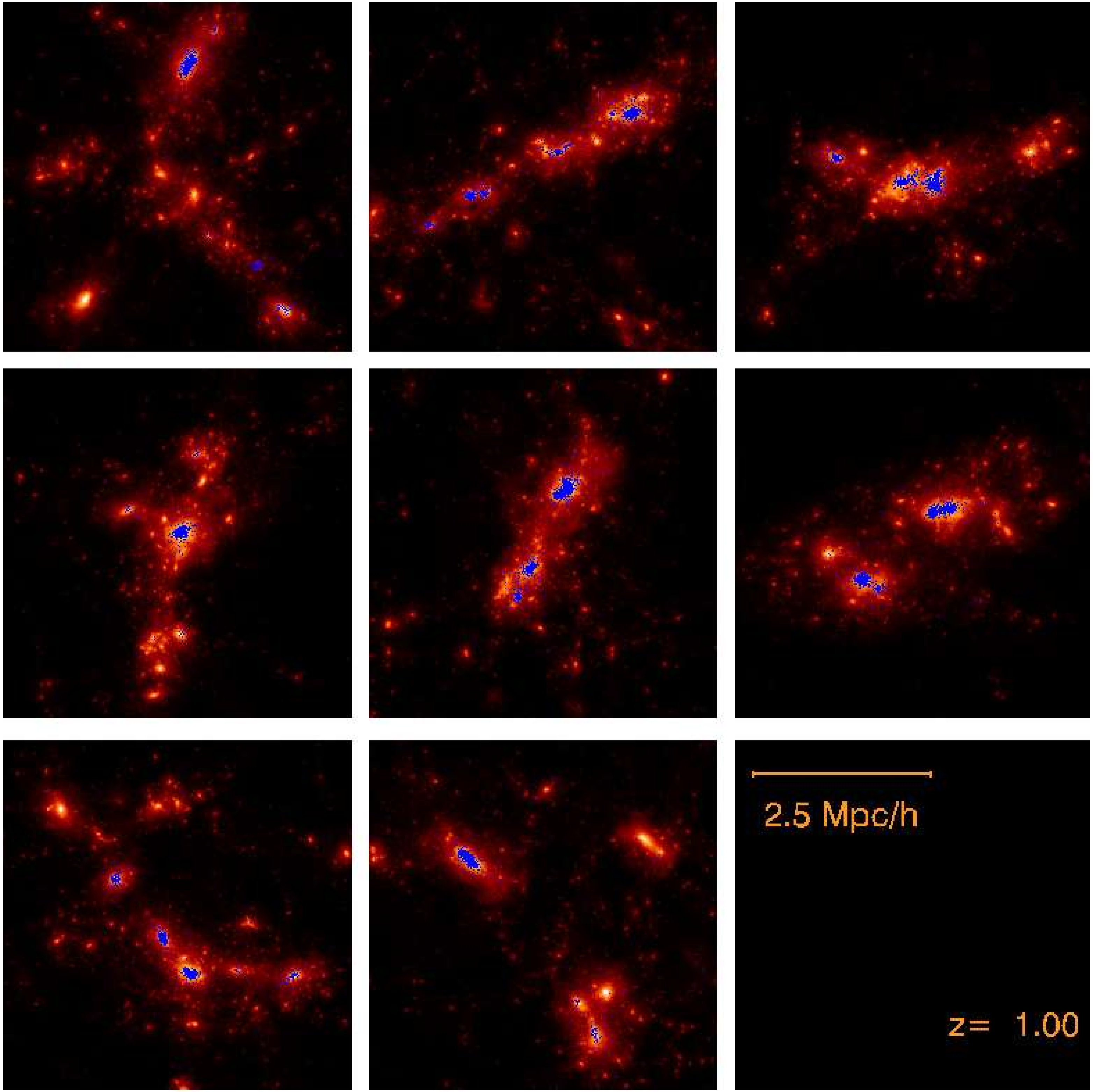
Sand, Treu & Ellis 2002





- Model potential as power law DM + galaxy with constant M/L
- Consistency with radial arc, tangential arc & velocity dispersion profile

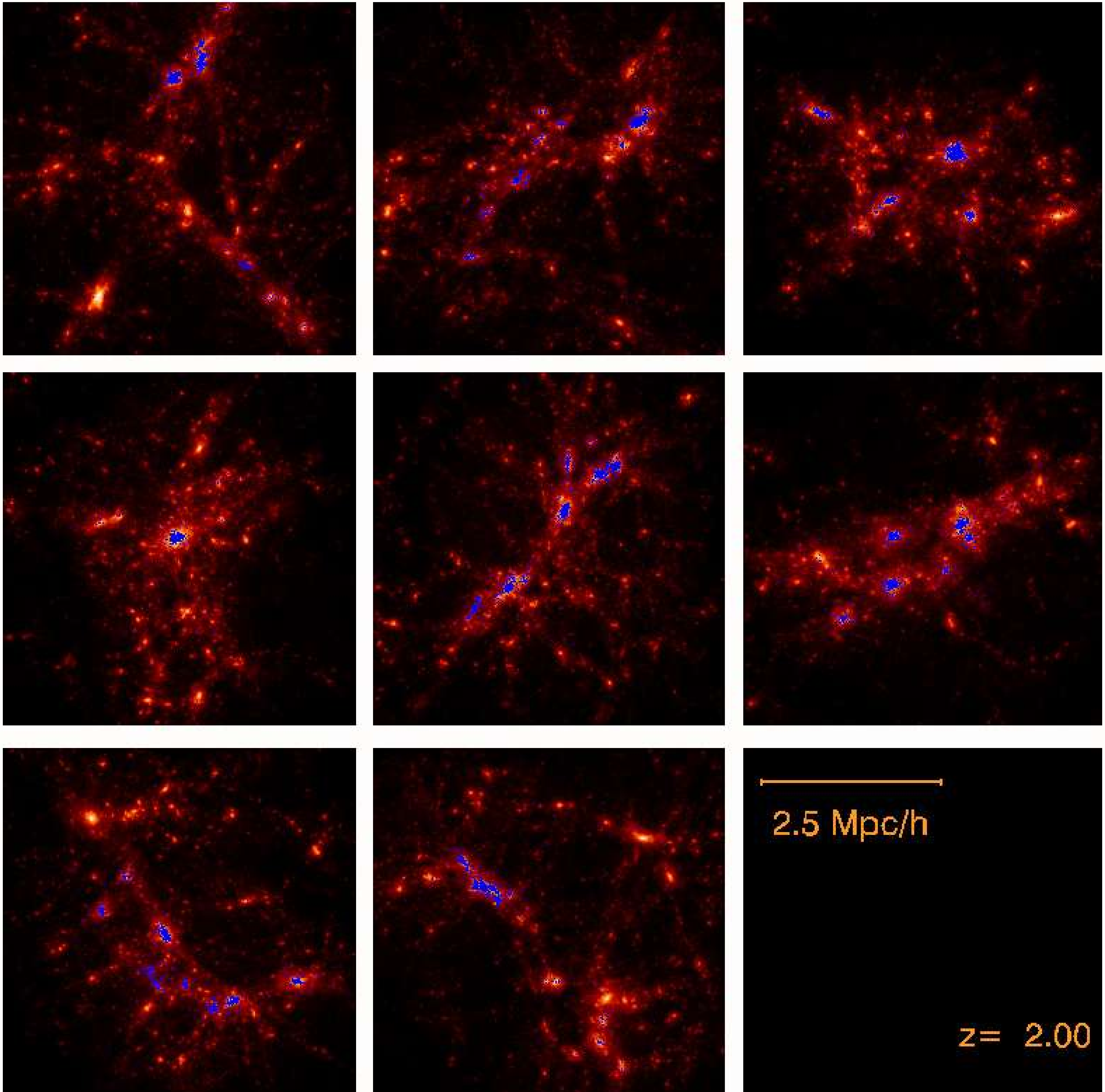
→ inner slope of DM profile shallower than NFW



Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass $\sim 10^{15}\, M_{\odot}$
- DM within 20kpc at $z = 0$ is shown blue

Cluster structure in ΛCDM



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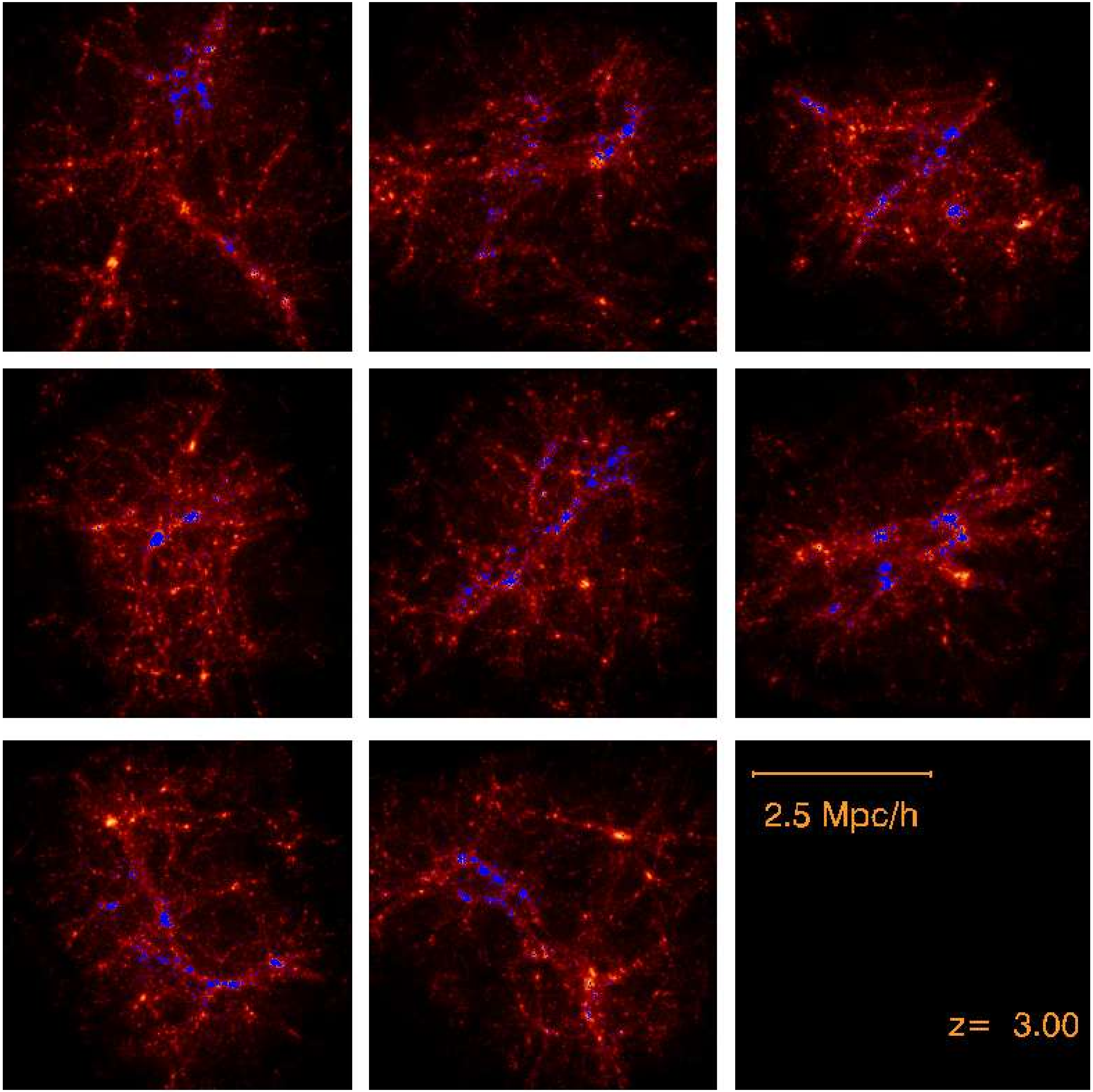


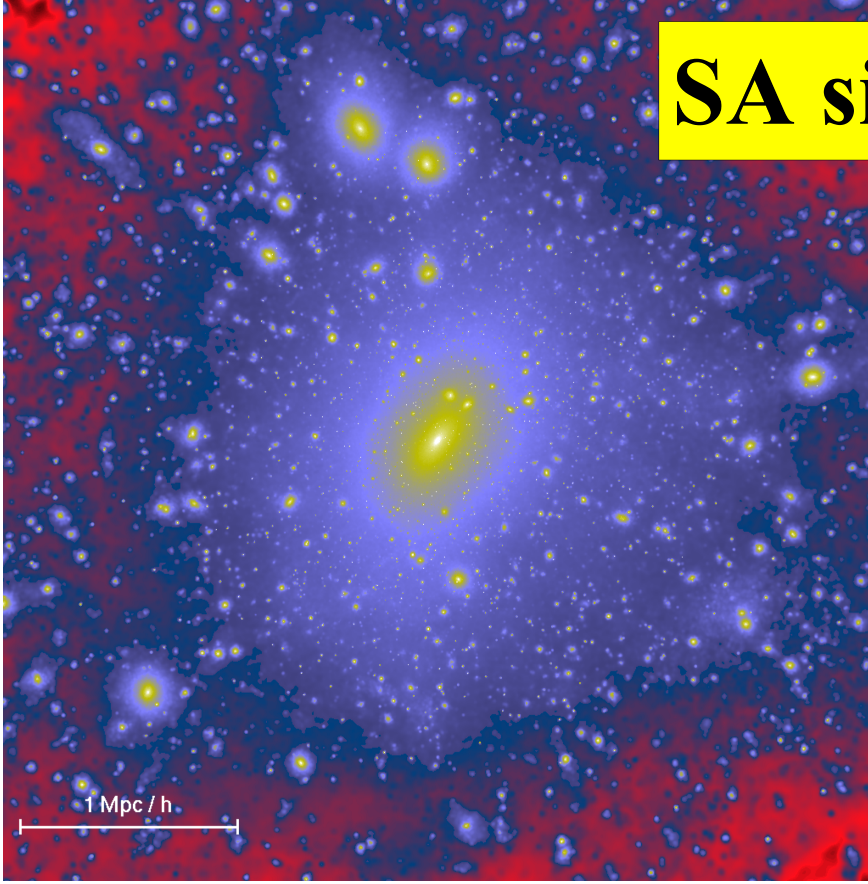
Cluster structure in ΛCDM

- 'Concordance' cosmology
- Final cluster mass ~10^{15} $M_\odot$
- DM within 20kpc at z = 0 is shown blue

Galaxy formation in the standard paradigm

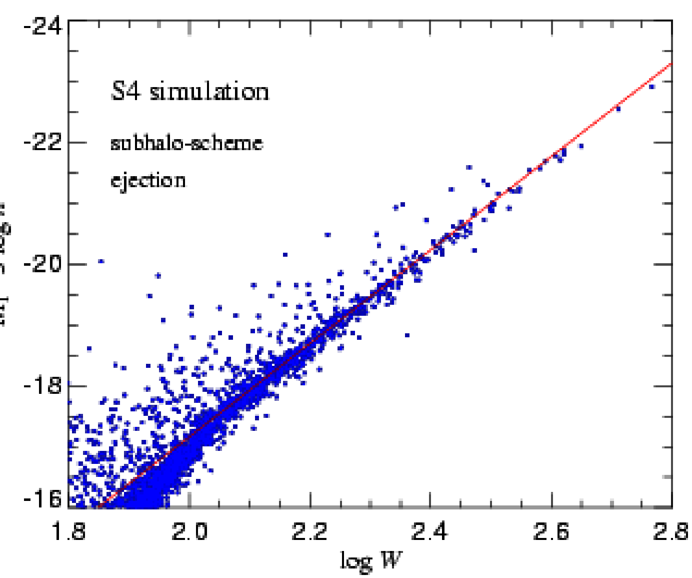
- Nonlinear dark matter clustering under gravity
  → hierarchical "dark halo" growth by accretion and merging
- Infall and shock heating of diffuse gas
  → hot gas "atmospheres" in halos (e.g. the intracluster gas)?
- Cooling and condensation of gas into "protogalaxies"
  → rotationally supported disks?
- Star formation in disks or during protogalactic collapse
  → disk galaxies or "primordial" spheroids
- Feedback from UV radiation and galactic winds
  → reionisation and enrichment of the intergalactic medium
  regulation of star formation within galaxies
- Merging of galaxies
  → starbursts
  morphological transformation : disks → spheroids

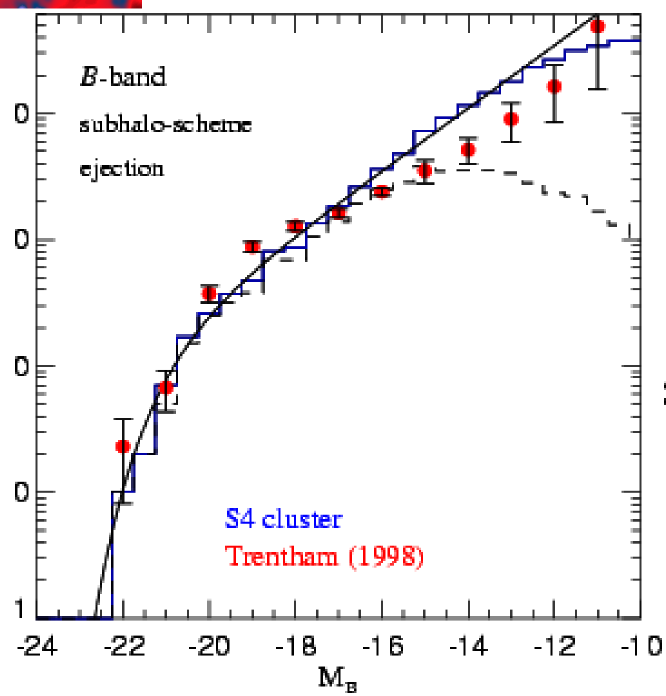
SA simulation of cluster formation

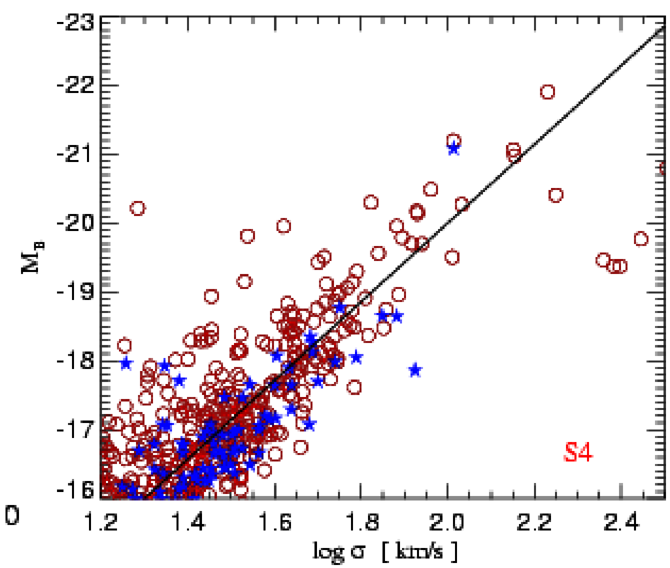


- Semi-analytic methods allow the simulation of a Coma cluster following all galaxies with $M_B < -12$
- Nearly all galaxies with $M_B < -16$ retain their own dark halos
- Protocluster can be analysed at high z

Springel et al 2001



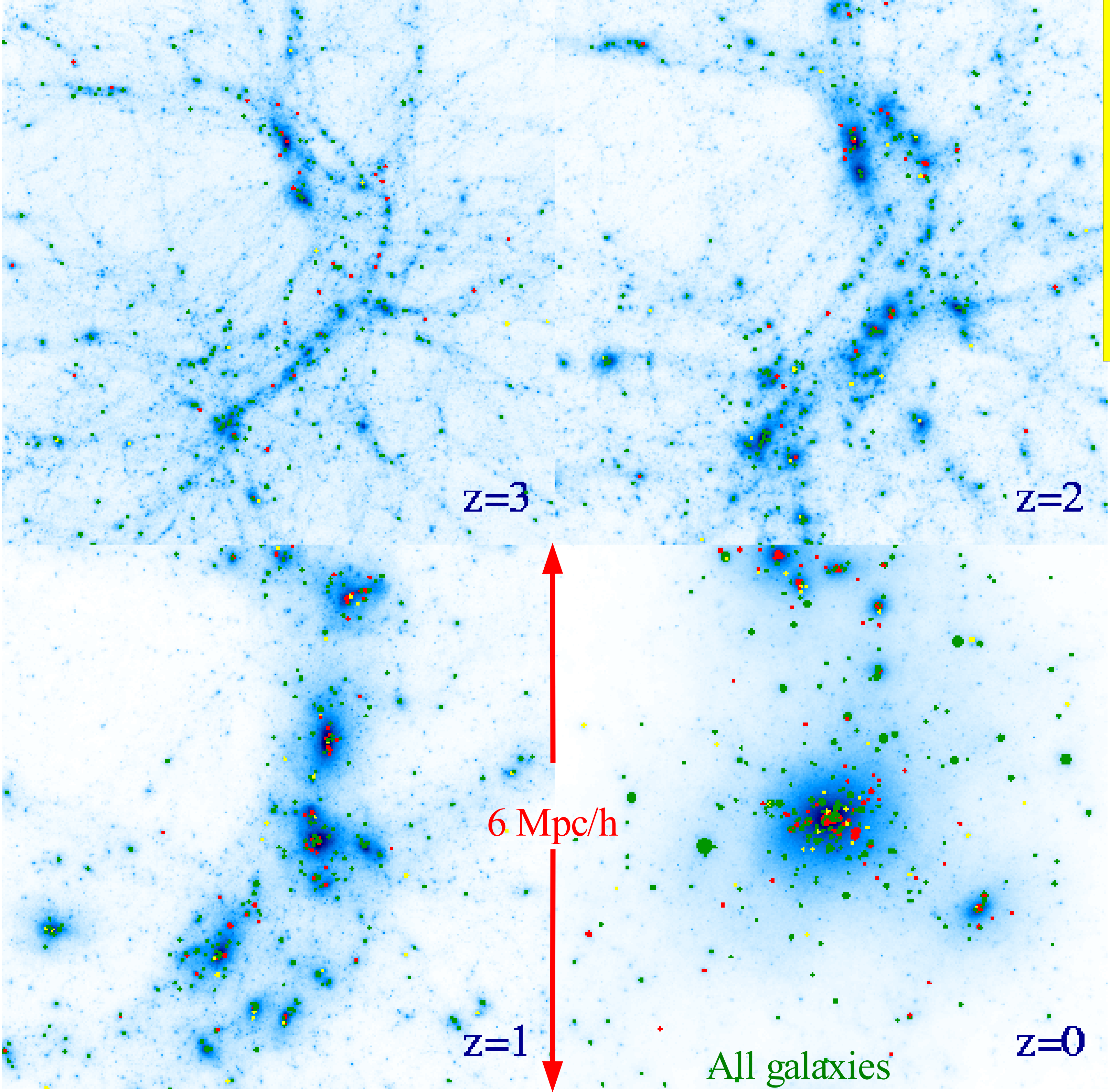




Evolution of the galaxy population in a Coma-like cluster

Springel et al 2001

- Formation of the galaxies tracked within evolving (sub)halos
- Luminosity and mass of galaxies is uncertain
- Positions and velocities are followed well



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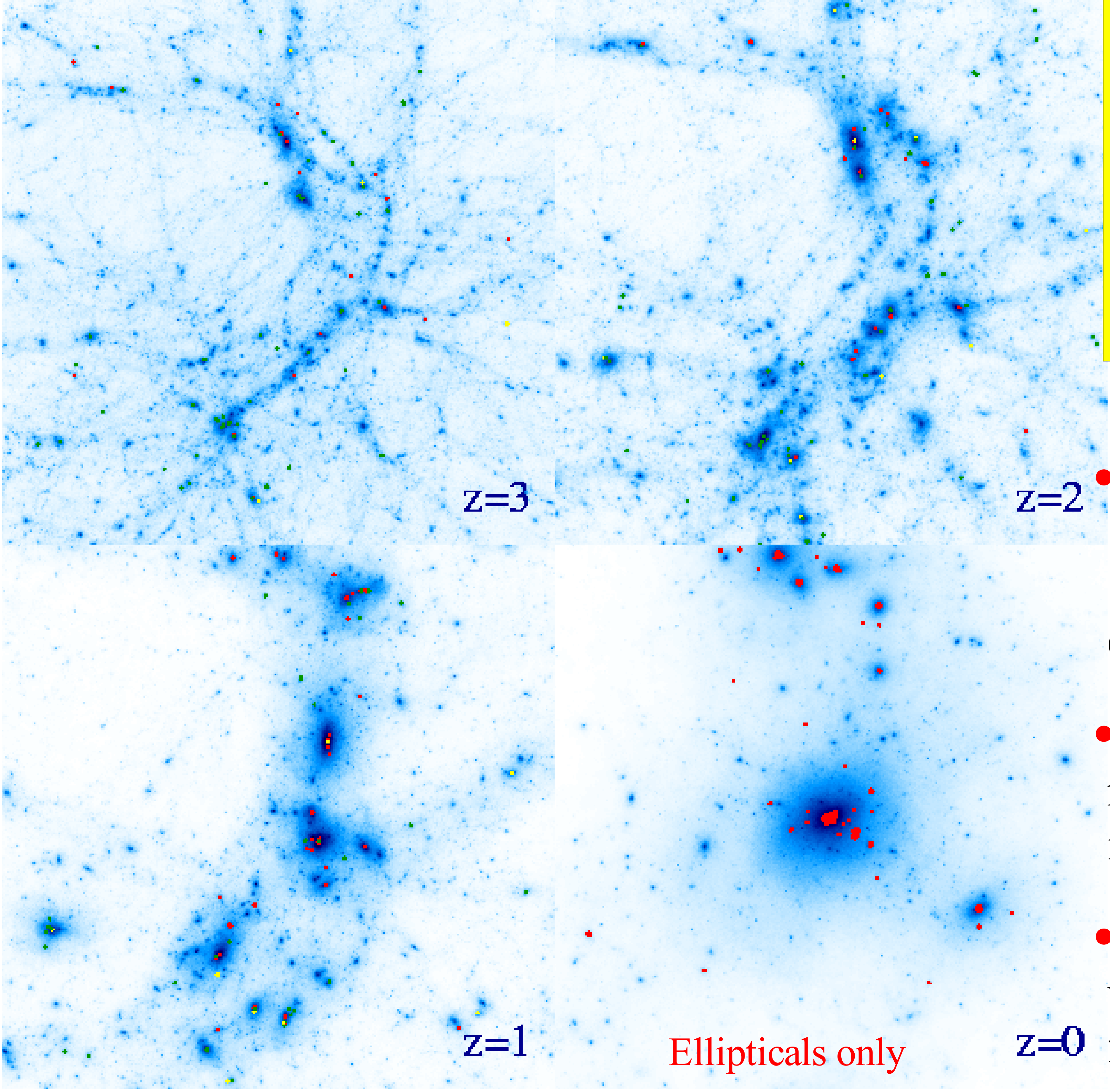

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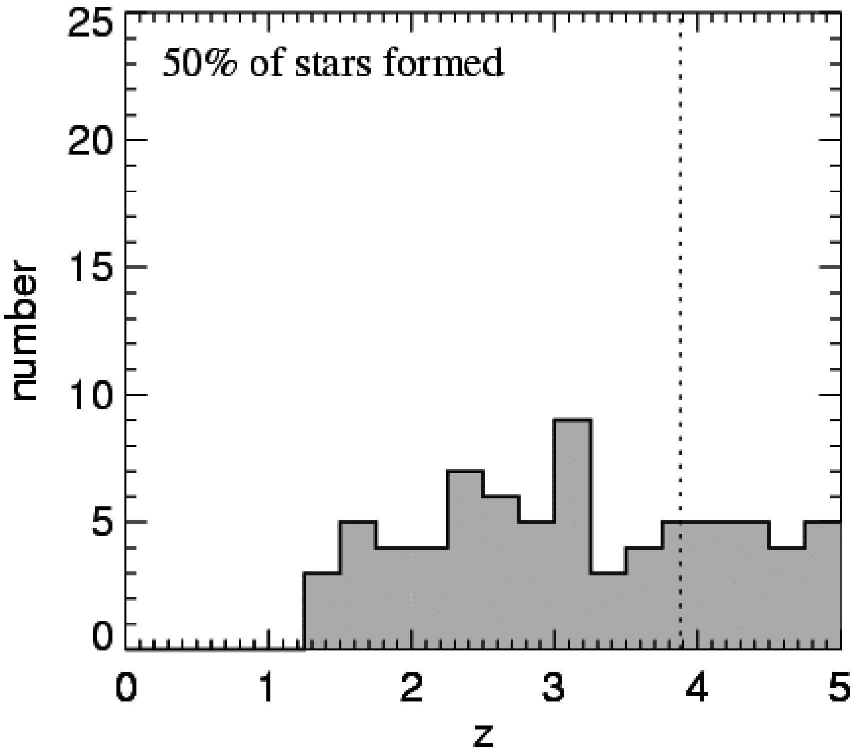
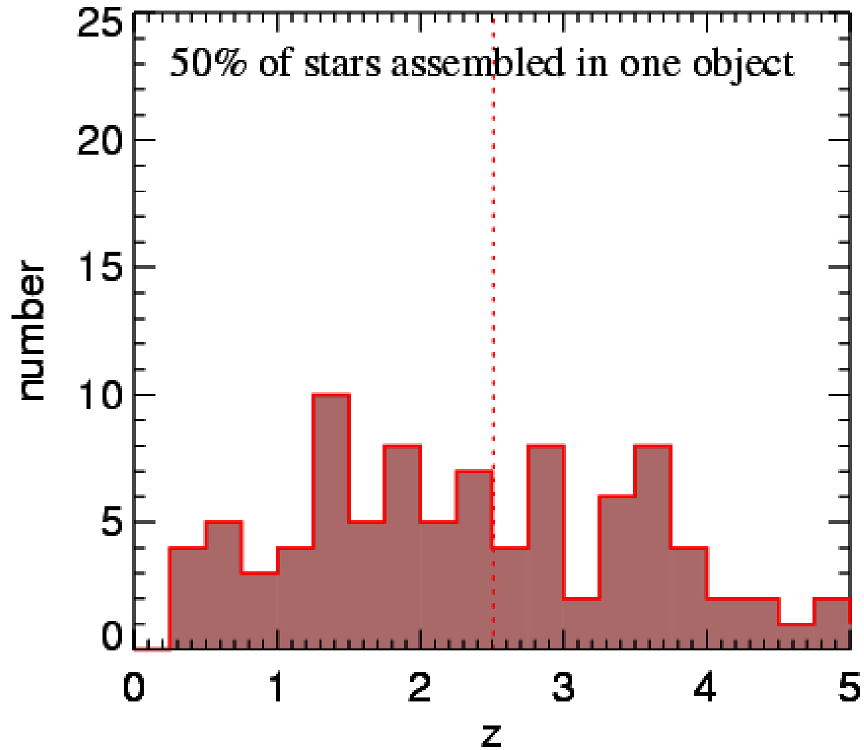
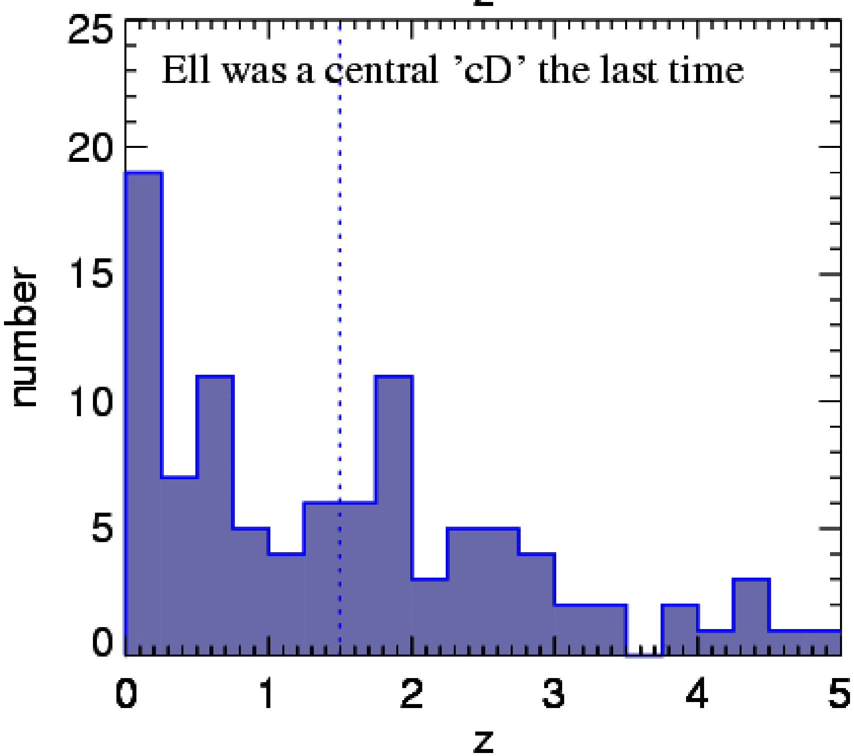


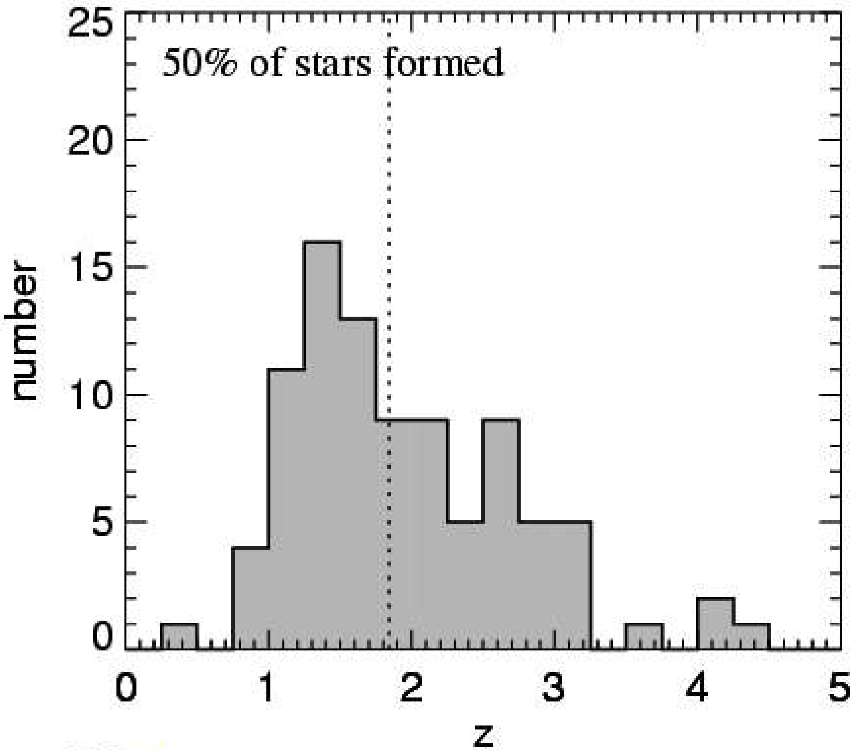


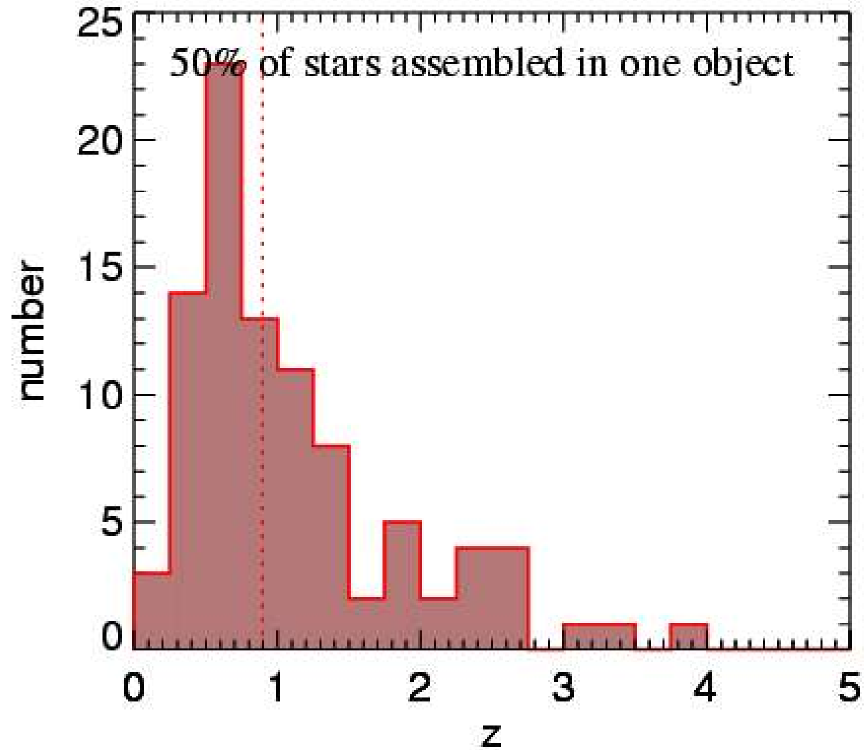
Springel et al 2003



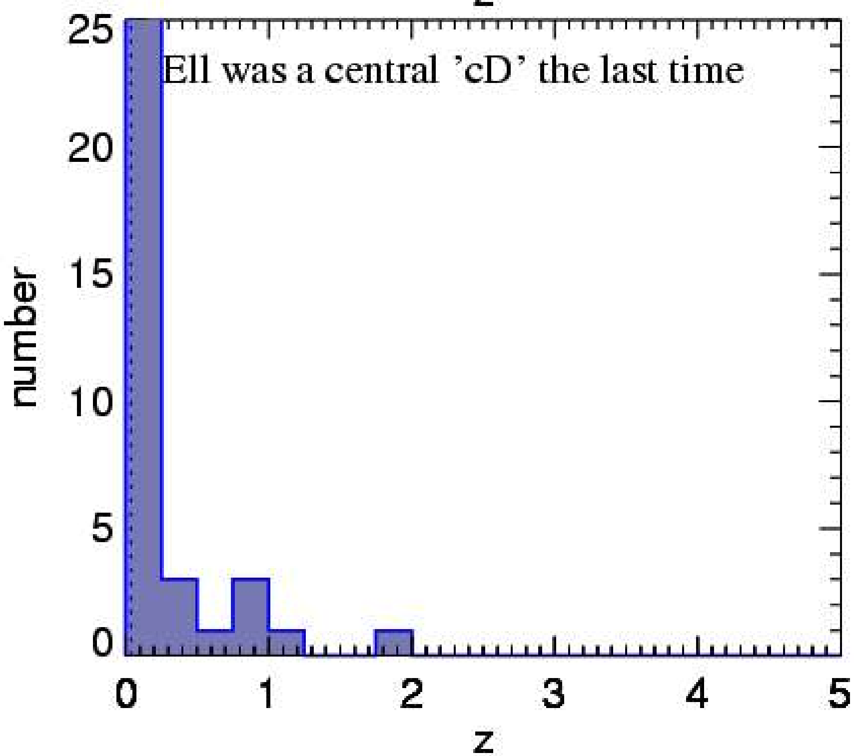
Formation histories of cluster ellipticals

- Cluster mass is $7 \times 10^{14} M_{\odot}/h$
- 104 member ellipticals with $M_B < -18$
- Stars form early
- Most ellipticals assembled early
- Many ellipticals accreted late





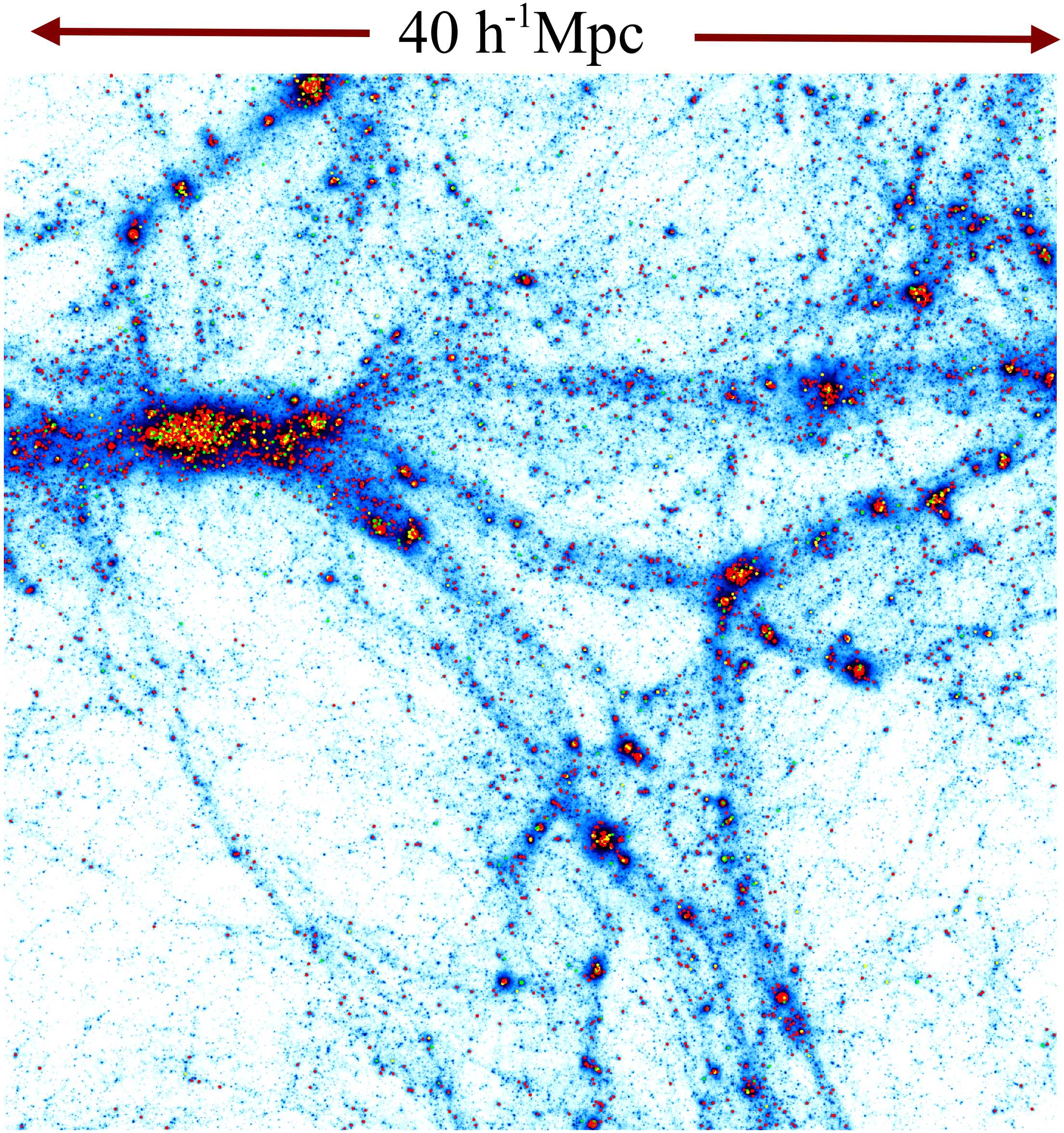
Springel et al 2003

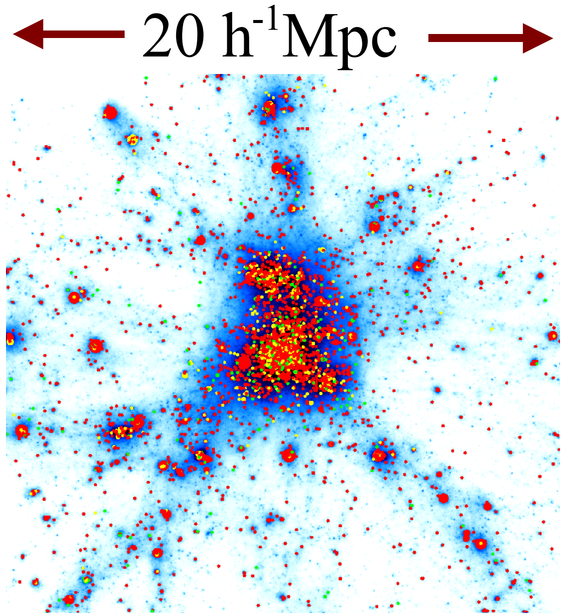


Formation histories of field ellipticals

- 91 field ellipticals with $M_B < -18$
- Stars form fairly early
- Most ellipticals assembled late
- Most ellipticals are 'cD' of their groups

Field vs cluster evolution of the galaxy population





$\rho_* = 3.5 \langle \rho_0 \rangle$

$\rho_* = 0.9 \langle \rho_0 \rangle$

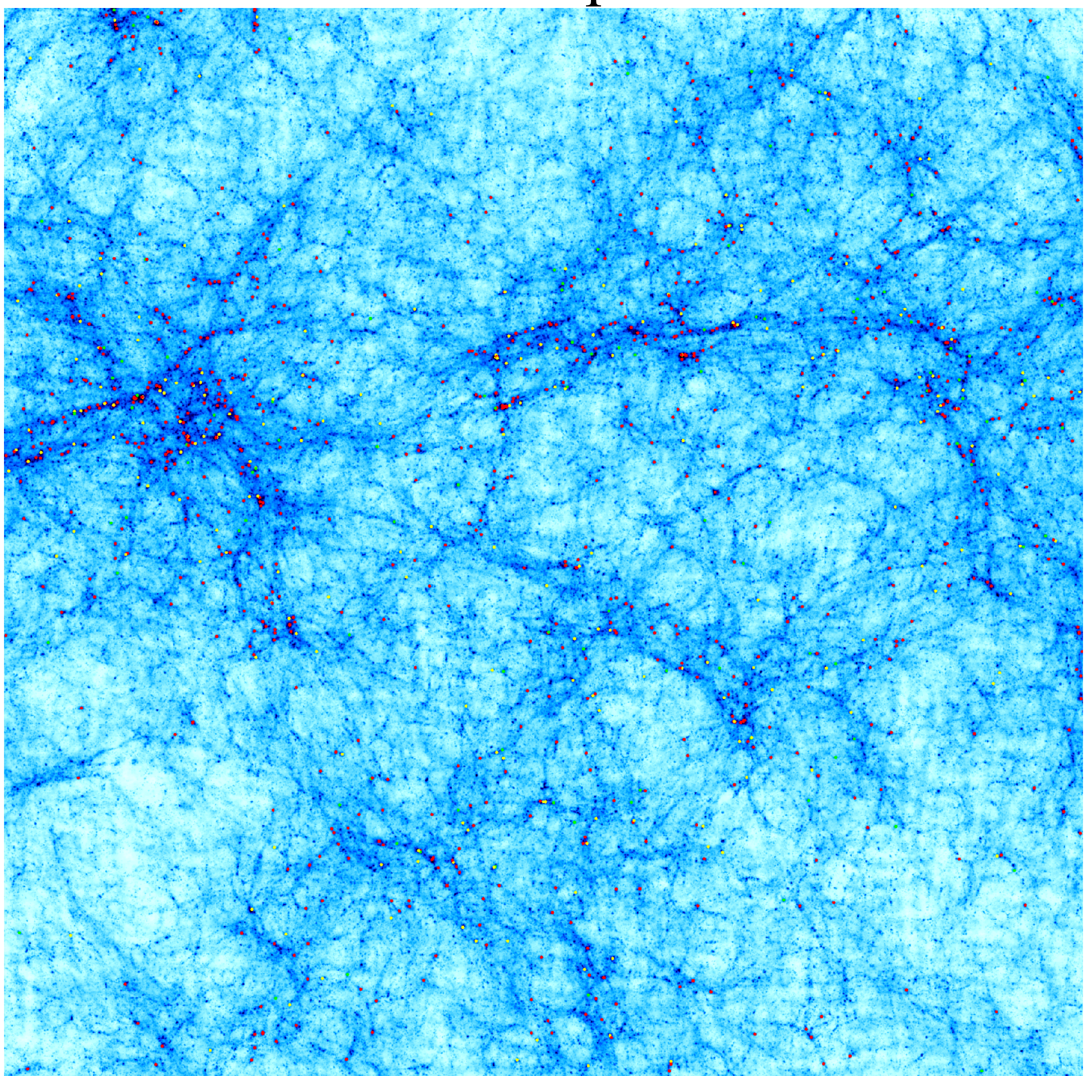
$M_{gal} > 10^9 M_{sun}$

$z = 0$

Stoehr et al 2002

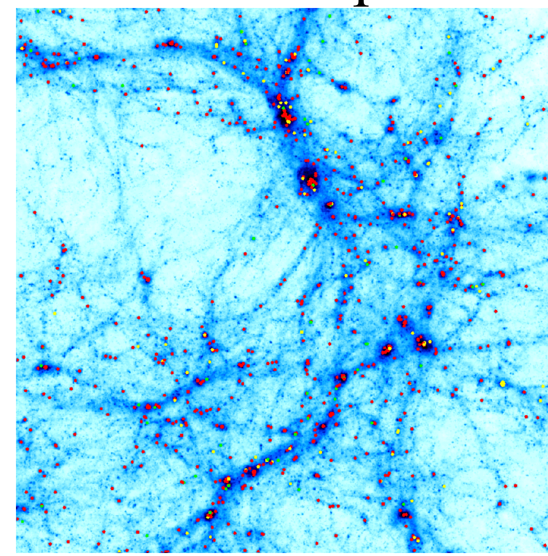
Field vs cluster evolution of the galaxy population

$\longleftarrow$ 40 h^{-1}Mpc $\longrightarrow$



$$\rho_* = 0.17 \langle \rho_0 \rangle$$

$\longleftarrow$ 20 h^{-1}Mpc $\longrightarrow$



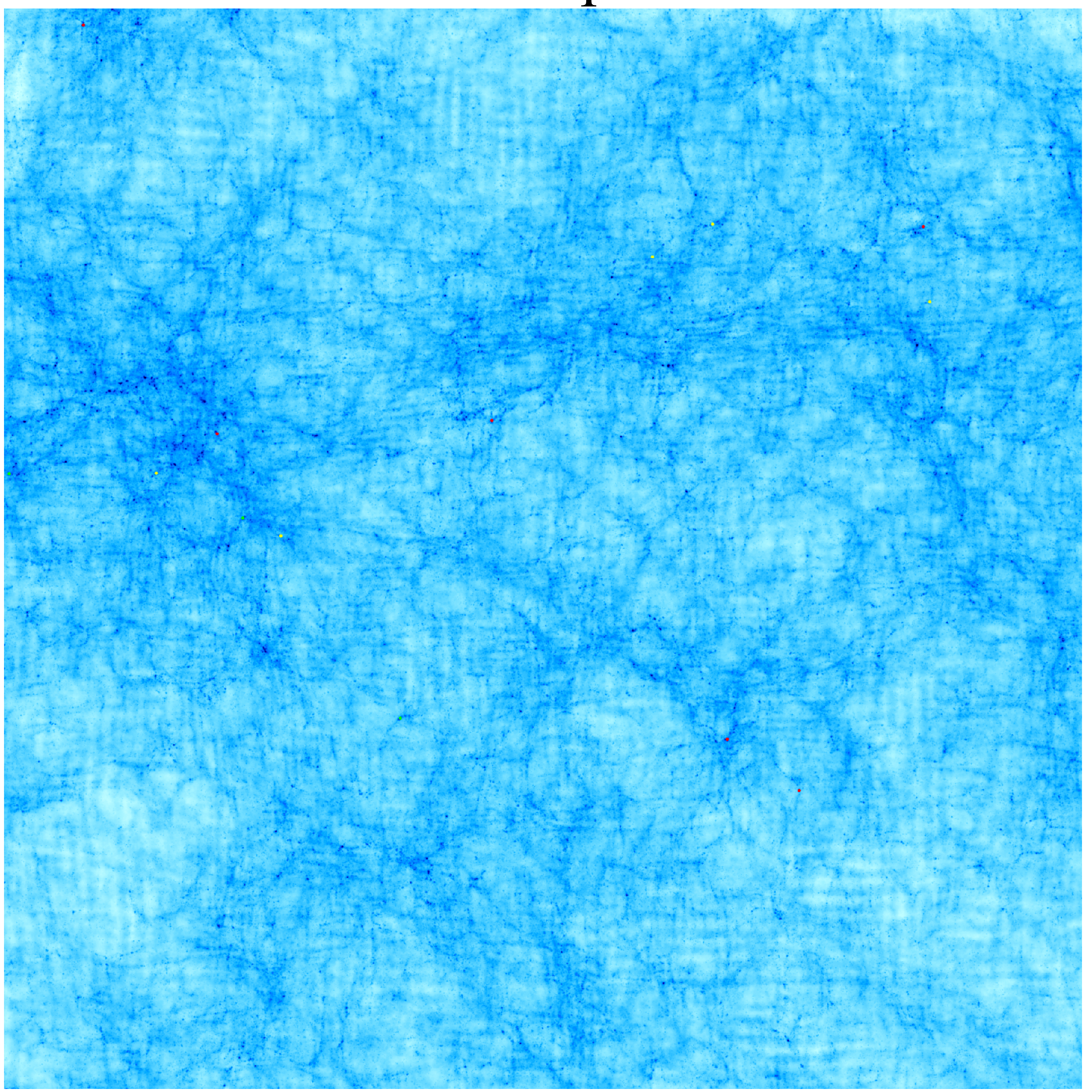
$$\rho_* = 0.5 \langle \rho_0 \rangle$$

$$M_{gal} > 10^9 M_{sun}$$

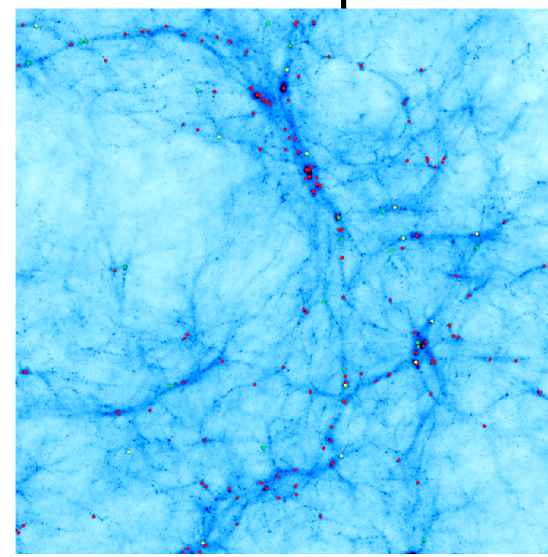
$z = 5$

Field vs cluster evolution of the galaxy population

40 h^{-1}Mpc



20 h^{-1}Mpc



$\rho_* = 0.093 \langle \rho_0 \rangle$

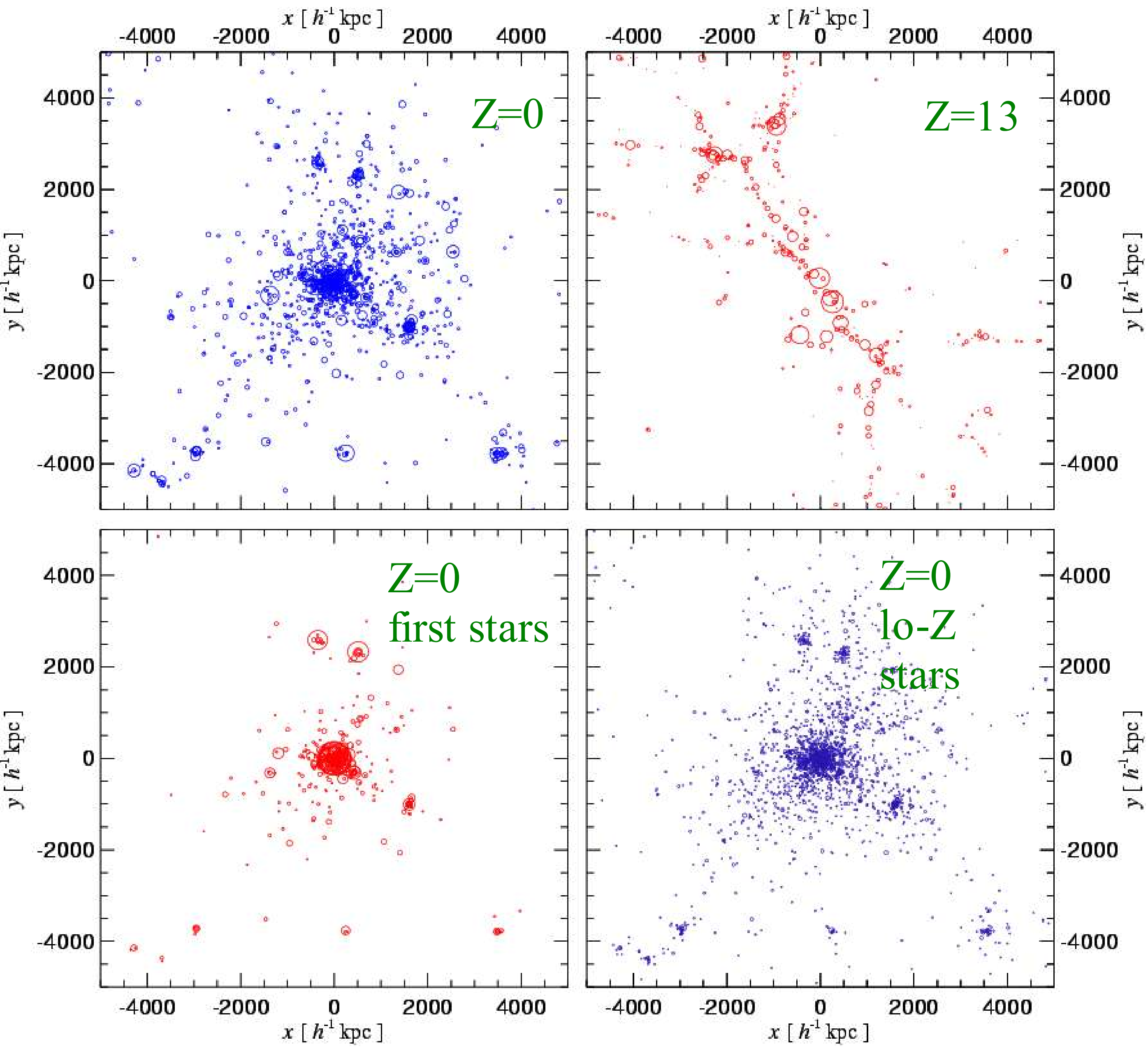
$\rho_* = 0.018 \langle \rho_0 \rangle$

$M_{gal} > 10^9 M_{sun}$

$z = 10$

Where are the first stars now?

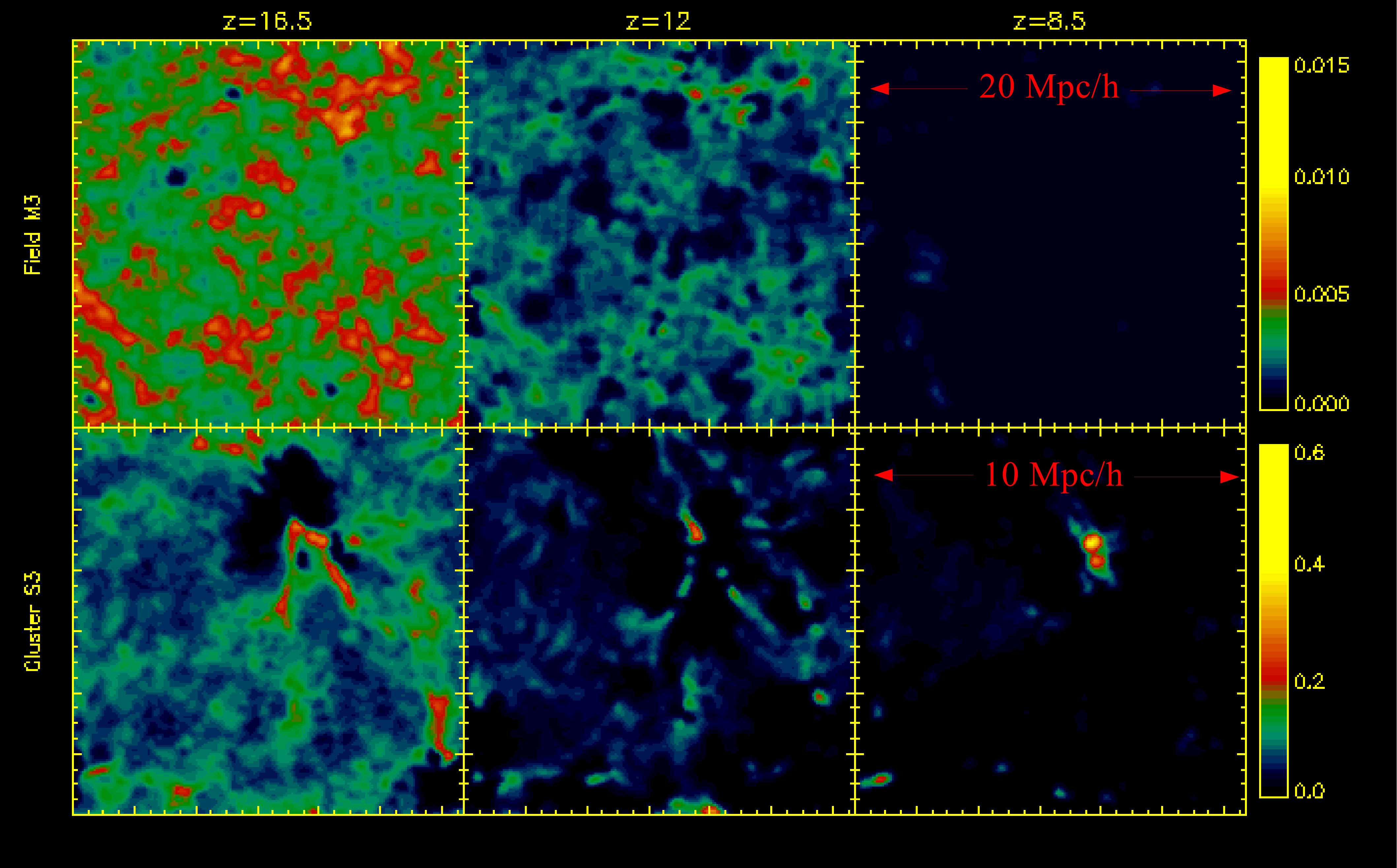
White & Springel 1999



- By z=13 about 1% of the stars that end up in a rich cluster have already formed
- These stars are to be found in galaxies that are *already* in large-scale structures
- More than half of them end up in the final cD
- Stars formed in the *lowest mass* objects are distributed like typical stars

Reionization of cluster and field regions

Ciardi, Stoehr & White 2003



Optical depth to electron scattering in comparison to *WMAP*

- Reionisation efficiency depends on:

  $\epsilon_{\text{massive * form.}} \times \epsilon_{\gamma\ \text{prod.}} \times \epsilon_{\text{escape}}$

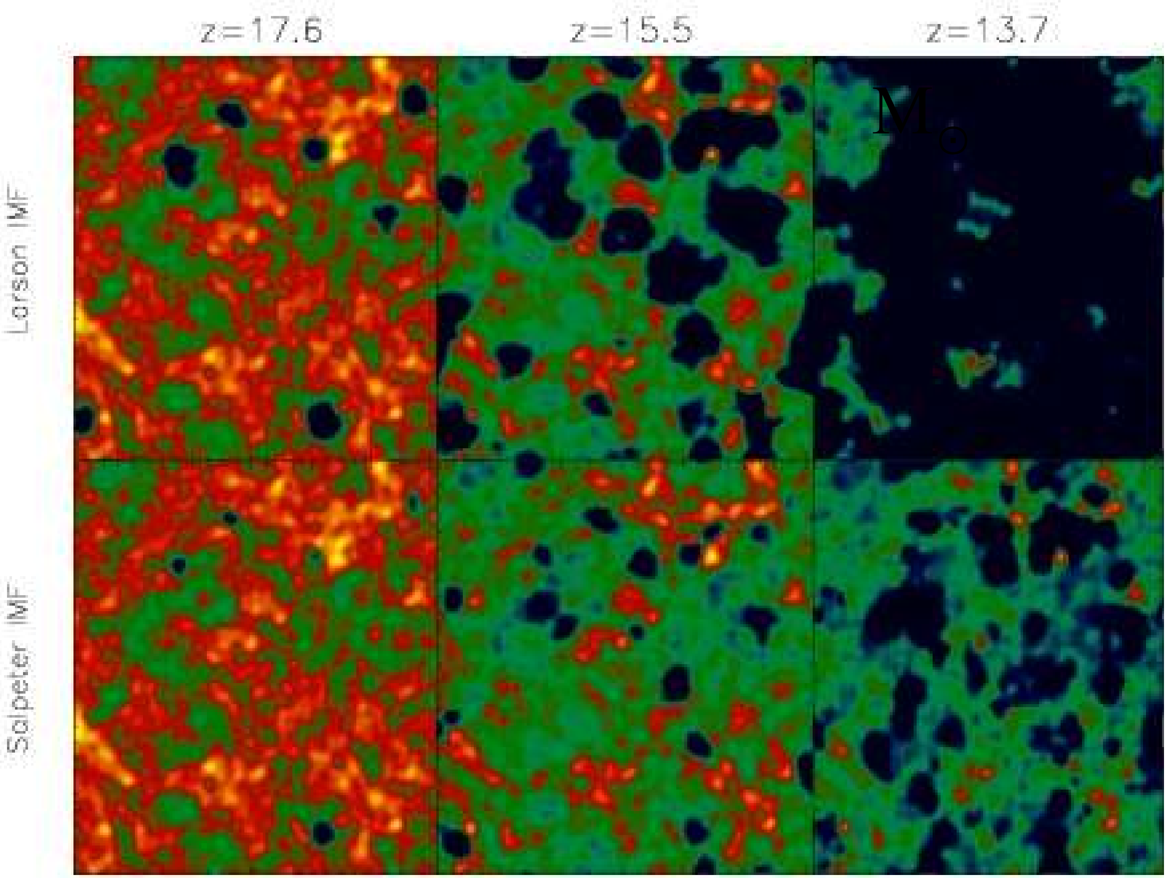
- Optimistic but physically plausible efficiencies reproduce the *WMAP* τ_e

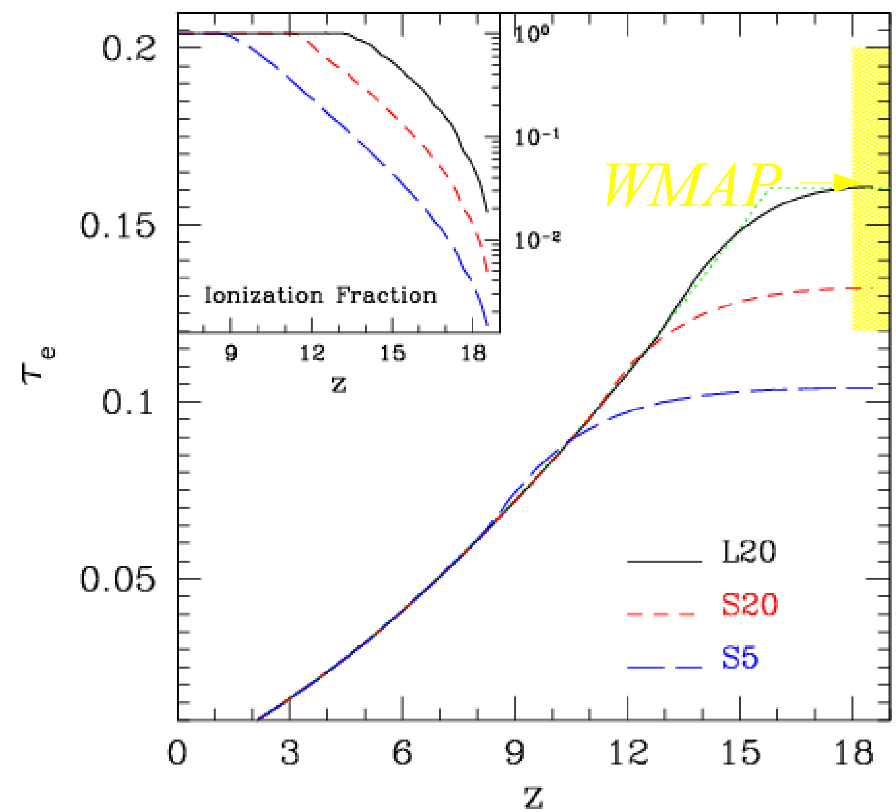
  without -- miniquasars

  -- H_2 cooling/Pop III stars

  -- galaxies with $M_{tot} < 10^9\ M_\odot$

Ciardi, Ferrara & White 2003





Cluster formation and evolution

- The initial conditions for cluster formation are now known down to scales much smaller than those responsible for building individual cluster galaxies
- Cluster assembly, even that of the innermost cluster core, occurred late, at $z < 1$ in most cases
- Clusters form by the infall of clumps along filaments
- Cluster assembly began early. The first cluster stars formed at $z > 40$. 1% may have formed by $z \sim 15$. The first stars are now mostly in the central massive galaxy.
- Cluster galaxies form stars early, assemble later and fall into the cluster later still.
- At reionisation, the Universe was strongly structured on scales of 50 Mpc or more